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The Cost of Removing Chloroform and Other Trihalomethanes from Drinking Water Supplies

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March 1977

THE COST OF REMOVING CHLOROFORM AND OTHER TRIHALOMETHANES FROM DRINKING WATER SUPPLIES

by

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

Trihalomethanes in general, and chloroform - a known carcinogen - in particular, are found in drinking water as a direct consequence of the practice of chlorination, a long established public health practice for the disinfection of drinking water. EPA would like to minimize the drinking water consumer's exposure to trihalomethanes at reasonable cost. This report is devoted to the presentation of the results from a research study which examines the costs of the various treatment technologies suited to the removal and control of trihalomethanes in drinking water.

Francis T. Mayo
Director
Municipal Environmental Research Laboratory

PREFACE

The Safe Drinking Water Act of 1974 has intensified the public awareness and interest in the quality of drinking water as delivered to the consumer's tap. The Act establishes a set of enforceable, health-related regulations and a set of non-enforceable esthetics-related guidelines for drinking water. For each health-related standard the Act establishes an associated Maximum Contaminant Level (MCL) that must not be exceeded. The Act also contains provisions for the EPA Administrator to take various courses of action when a contaminant is detected for which no MCLs have been established. Trihalomethanes in general, and chloroform, recently determined to be a carcinogen in drinking water, in particular, are examples of such contaminants.

Trihalomethanes are found in drinking water as a direct consequence of the practice of chlorination, a long established public health practice for the disinfection of drinking water supplies. Recent research has demonstrated that the concentration of chloroform and related compounds is generally higher in finished than in raw water, leading to the conclusion that they are being produced during the chlorination process.

Acting on these findings, Russell Train, Administrator of the U. S. Environmental Protection Agency, directed that EPA work with cities and states to evaluate certain modifications to current treatment practices that can reduce the formation of chloroform during the water treatment process, without lessening the effectiveness of disinfection. Part of this effort has been the preparation of a document, entitled "Interim Treatment Guide for the Control of Chloroform and Other Trihalomethanes in Drinking Water." The "Guide" has been prepared in an attempt to present EPA's knowledge concerning the removal and control of chloroform and other trihalomethanes in drinking water. It covers such items as: changing the point of chlorine application to reduce chloroform concentrations; the use of alternative disinfectants, such as ozone or chlorine dioxide; and the use of granular activated carbon as a medium for the adsorption of organic compounds.

Appendix I of the "Guide" presents cost information with respect to the use of granular activated carbon, ozonation, aeration, and chlorine dioxide for trihalomethane removal. This report was originally Appendix I of the "Interim Treatment Guide for the Control of Chloroform and Other Trihalomethanes," and provides an in-depth examination of the costs related to the above-mentioned techniques.

ABSTRACT

This research effort was conducted to provide an in-depth examination of the costs associated with the use of activated carbon, ozonation, aeration, and chlorine dioxide for removal of trihalomethanes.

The costs presented in this report are intended for the development of planning estimates only and not for the preparation of bid documents or detailed cost estimates. Exact capital and operating costs are highly variable from location to location within the United States, even for plants of the same size and design. These costs are presented in such a way as to enable the planner to make adjustments to the reported costs when local information is available. Standardized levels for a selected set of design parameters are assumed and sensitivity analysis is performed for the majority of the parameters.

Because chlorine is associated with the formation of trihalomethanes, several technological alternatives which may be used in lieu of or in combination with chlorination are examined. Costs are presented for the chlorination process itself. Costs are also calculated for ozonation, chlorine dioxide, aeration, and granular activated carbon. An in-depth analysis of the costs associated with granular activated carbon systems is presented. This analysis includes costs both with and without separate contactor systems and an examination of the possible cost savings associated with regional regeneration.

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METRIC CONVERSION TABLE

English Units	Metric Equivalents
1 foot	0.305 meters
1 mile	1.61 kilometers
1 square mile	2.59 square kilometers
1 million gallons	3.79 thousand cubic meters
1 $/million gallons	0.26 $/thousand cubic meters
1 ¢/1000 gallons	0.26 ¢/cubic meter

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THE COST OF REMOVING CHLOROFORM AND OTHER TRIHALOMETHANES FROM DRINKING WATER SUPPLIES

BY

Robert M. Clark*, Daniel L. Guttman+, John L. Crawford+, and John A. Machisko+

INTRODUCTION

The Safe Drinking Water Act of 1974 will change the way water is handled before it is distributed to the consumer.[10] The Act contains two types of provisions for drinking water as delivered to the consumer's tap: a set of enforceable regulations that are health-related, and a set of non-enforceable guidelines that are related to the esthetics of drinking water. Each health-related standard has an associated Maximum Contaminant Level (MCL) that must not be exceeded. The Act also contains provisions for the Administrator, U. S. Environmental Protection Agency (EPA) to take various courses of action when a contaminant is detected for which no MCLs have been established.[1] Trihalomethanes in general and chloroform in particular, recently determined to be a carcinogen in drinking water, are examples of such contaminants.

Trihalomethanes are found in drinking water as a direct consequence of the practice of chlorination, a long established public health practice for the disinfection of drinking water. It is probable that chlorine has been reacting with certain organic materials to produce chloroform and related organic byproducts since chlorination was initiated. These compounds in drinking water escaped detection due to their low concentrations and because of their low boiling points, which allowed them to be lost during procedures used for performing typical organic analyses in water.[12]

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Recently, investigators have developed new, more sensitive analytical procedures which allow for more precise measurement of trihalomethanes. The newly developed procedures have been used to demonstrate that the concentration of chloroform and related compounds is generally higher in finished than in raw water, leading to the conclusion that they are being produced during the chlorination process.

Acting on these findings, Russell Train, Administration of the U. S. Environmental Protection Agency, on March 29, 1976, released a statement that said in part, ". . . The recent test results and the fact that chloroform is prevalent in the environment have convinced me that the prudent course of action at this time is to minimize exposure to this chemical wherever it is feasible to do so." He also said, "EPA will work with cities and states to evaluate certain modifications to current treatment practices that can reduce the formation of chloroform during the water treatment process, without lessening the effectiveness of disinfection. EPA research has shown that changes in chlorination procedures practiced by some water systems can result in reduction in the levels of chloroform produced. EPA plans to share these initial findings on chloroform reduction with the states and some cities encountering high chloroform levels, in an effort to reduce human exposure as quickly as possible. This will also allow EPA to gain added information to support the development of national regulations to limit chloroform levels in water supplies."

An interim guide, entitled "Interim Treatment Guide for the Control of Chloroform and Other Trihalomethanes in Drinking Water," has been prepared in an attempt to present EPA's knowledge concerning the removal and control of chloroform and trihalomethanes in drinking water. The "Guide" covers such items as: changing the point of chlorine application to reduce chloroform concentrations; the use of alternative disinfectants, such as ozone or chlorine dioxide; and the use of granular activated carbon as a medium for the adsorption of organic compounds.

The "Guide" summarizes EPA's current knowledge and recent research results related to the removal and control of chloroform and other trihalomethanes. It also presents cost information with respect to the use of granular activated carbon, ozonation, aeration, and chlorine dioxide for trihalomethane removal. This report has been developed as a support document for the "Guide" and provides an in-depth examination of the costs related to the above-mentioned techniques.[14]

COST DETERMINATION

The costs presented in this report are intended for the development of planning estimates only and not for the preparation of bid documents or detailed cost estimates. Exact capital and operating costs are highly variable from location to location within the United States, even for plants of the same size and design. Variables -- such as local costs of land, materials, and labor; state or regional differences in building codes; and existing facilities suitable for modification -- may accentuate the differences in treatment costs for similar plants to reduce chloroform and other trihalomethanes in drinking water.

These cost data are presented in such a way as to enable the planner to make adjustments to the reported costs when local information is available. For example, operation and maintenance costs can be reduced if the delivered cost of chemicals is less than the costs upon which the estimates are based. Costs indices are used to provide a baseline for projecting costs and for estimating escalation due to inflation. The indices used in this report are national indices, but other indices are often available for major U. S. cities or on a regional basis and may be substituted if desired.

Basis of Cost Estimates

The cost indices used in this report are:

a. EPA's Sewer and Sewage Treatment Plant Construction Cost Index:[6] This index was used because most of the basic information utilized in the report was obtained from the Systems and Economic Evaluation Section of EPA's Wastewater Research Division.[9,3] For example, computations for granular activated carbon were performed using a computer program developed by the Systems and Economic Evaluation Section, but operational modifications were assumed in the analysis to reflect conditions unique to water supply.[11] The index should reflect similar costs for water treatment plant construction and for January 1976 is 256.7.

b. Wholesale Price Index:[2] The Wholesale Price Index (WPI) is the oldest continuous statistical series published by the Bureau of Labor Statistics (BLS). It is a measure of the price changes for goods sold in primary markets in the United States. "Wholesale," as used in the title of the index, refers to sales in large quantities, not prices received by wholesalers, jobbers, or distributors, and for January 1976 is 175.1.

c. Bureau of Labor Statistics Labor Cost Index (Direct Hourly Wage Rate):[5] The index used in this report is, for personnel in Standard Industrial Category (SIC), 494.7 for Water, Steam and Sanitary Systems Non-Supervisory Workers. The base BLS Labor Cost Index for February 1976 is 5.19.

Costs reported as Capital Costs include:

a. construction for site preparation,

b. plant construction,

c. legal, fiscal, and administrative services,

d. interest during construction, and

e. start-up costs.

Costs reported as Operating and Maintenance Costs include:

a. chemical costs,

b. labor costs, and

c. operation and maintenance costs, such as utilities, annual replacement of expendable items, etc.

Because the formation of trihalomethanes is associated with chlorination, several options will be considered in lieu of chlorination, all more expensive than the basic chlorination process itself. The benefits as well as the problems associated with changing to some alternative must be weighed when choosing another form of disinfection. For example, ozonation, while not creating chloroform, also does not provide any kind of residual disinfectant in the distribution system. Moreover, it is conceivable that the byproducts resulting from disinfecting with chlorine dioxide or ozone might be more harmful than chloroform itself. Granular activated carbon (GAC) is not a direct alternative to chlorination, but provides a means of removing organics from water supplies. The cost of the processes to be considered - chlorine dioxide, ozonation, and granular activated carbon - must be weighed against the basic cost of chlorine disinfection. Initially, the costs associated with chlorination will be presented. Next, the directly competitive disinfection alternatives of chlorine dioxide and ozonation will be discussed. The cost of aeration as a means of removing chloroform and other trihalomethanes once they have been formed and, finally, a cost analysis for granular activated carbon as a general means of removing organics will be presented.

COST OF CHLORINATION

Chlorine was first used as a disinfectant for municipal water supplies in the United States in 1908 to disinfect continuously the water supply of Jersey City, New Jersey.[4] In many water supplies, chlorination is often the only treatment process used. When other treatment methods are used, disinfecting chlorine may be added to the raw water (prechlorination), the partially treated water, or the finished water (postchlorination). Where the distribution system contains open reservoirs, the treated water may be rechlorinated in the distribution system.

In this analysis, a number of variables have been evaluated as to their effect on the cost of chlorination. Baseline or standardized design values for a set of design parameters were assumed and the cost of chlorination, including chlorine feeding equipment and contact chambers for 1, 5, 10, 100, and 150 million gallons per day (mgd) systems, was calculated. The parameters and their associated "standardized" levels are shown in Table 1.

Figure 1 shows the effect of economies of scale, by displaying the total amortized unit cost of a chlorination system in ¢/1000 gal versus plant capacity, based on the values in Table 1. It can be seen that cost varies from 3.6¢/1000 gal at 1 mgd to 0.6¢/1000 gal at 150 mgd. Figure 2 separates the total unit costs shown in Figure 1 into unit Amortized Capital and O & M costs.

TABLE 1. DESIGN PARAMETERS FOR THE COST OF CHLORINATION

Design Parameter (Variable)	Level
Chlorine Dose	2 mg/l
Chlorine Contact Time	20 min
Cost of Chlorine	300 $/ton
Construction Cost Index	256.7
Wholesale Price Index	178.1
Direct Hourly Wage Rate	5.19 $/hr
Amortization Interest Rate	7 percent
Amortization Period	20 yr
Electric Power Cost	$0.01/KWH
Design Parameter (Fixed)	
Capacity Factor	70 percent

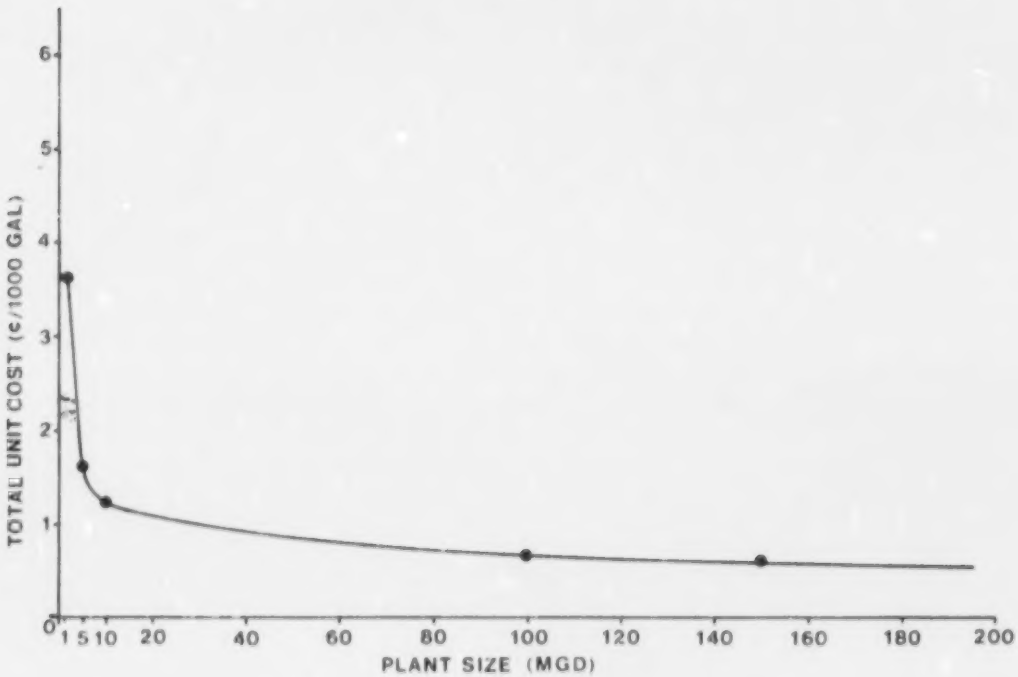

FIGURE 1. UNIT COST FOR CHLORINATION VERSUS PLANT SIZE

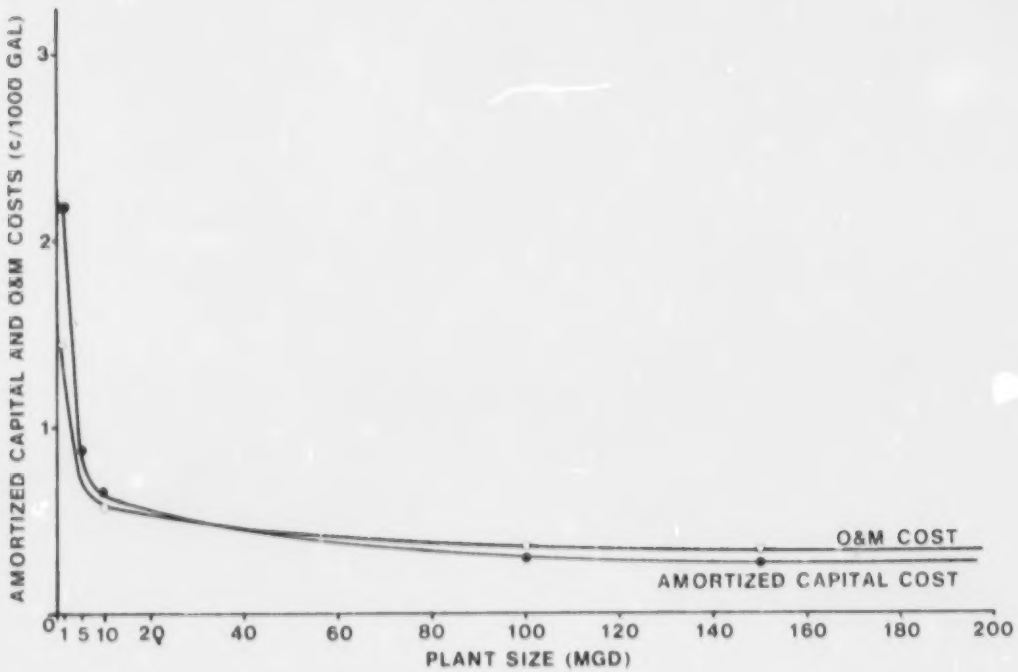

FIGURE 2. CAPITAL AND O&M COSTS FOR CHLORINATION VERSUS PLANT SIZE

Figures 3 through 11 show the sensitivity of the cost of chlorination to variations in all of the design variables listed in Table 1, with the exception of capacity factor. Capacity factor has been fixed at 70 percent to reflect the fact that water treatment systems generally operate at less than design capacity. Costs presented in this report, therefore, reflect the average costs to be expected over a year's operating period. The sensitivity analysis assumes that one parameter is varied while the others are fixed at the standardized levels, and is an attempt to show how costs might vary due to local conditions.

The parameters which affect only O & M cost are shown in Figures 3, 4, and 5 as follows: cost of chlorine, direct hourly wage rate, and wholesale price index. It can be seen that all of the parameters have a significant impact on O & M cost. For example, for a 100 mgd plant, increasing the cost of chlorine from 300 $/ton to 400 $/ton increases the O & M cost from 0.36¢/1000 gal to 0.46¢/1000 gal (28 percent). For a 1 mgd plant, increasing the Direct Hourly Wage Rate from 5.19 $/hr to 6 $/hr raises the O & M cost from 1.40¢/1000 gal to 1.56¢/1000 gal (11 percent).

The parameters which affect Amortized Capital costs are as follows: chlorine contact time, interest rate, construction cost index, and amortization period. The effects of these variables are shown in Figures 6, 7, 8, and 9.

The parameter (aside from the load factor) which affects both Amortized Capital and O & M costs is chlorine dosage and is shown in Figures 10 and 11. It can be seen that an increase of 1 mg/l dosage of chlorine increases the O & M cost alone by 0.15¢/1000 gal for a 100 mgd plant. Table 2 summarizes the cost of chlorination for 1, 5, 10, 100, and 150 mgd systems in ¢/1000 gal assuming the levels of the design variables as shown in Table 1.

As can be seen from the previous analysis, chlorination costs are relatively stable. Another form of disinfection is chlorine dioxide disinfection which will be discussed in the following section.

COST OF CHLORINE DIOXIDE

An alternative to chlorine is chlorine dioxide, which does not produce measurable quantities of trihalomethane, however, there is a possibility of toxic organic byproducts resulting from the reaction of chlorine dioxide with organic matter in water.[7] In this cost analysis, it was assumed that half the dosage of chlorine dioxide as compared to chlorine is required to achieve equivalent disinfection results. Therefore, it was assumed that 1 mg/l of chlorine dioxide would achieve disinfection results equivalent to those achieved by 2 mg/l of chlorination. If 0.5 mg/l of chlorine is combined with 1.6 mg/l of technical grade sodium chlorite, a 1 mg/l dosage of chlorine dioxide will result. The equation below shows this relationship (assuming 80 percent pure $NaClO_2$ yields 1.3 mg/l of reactive material):

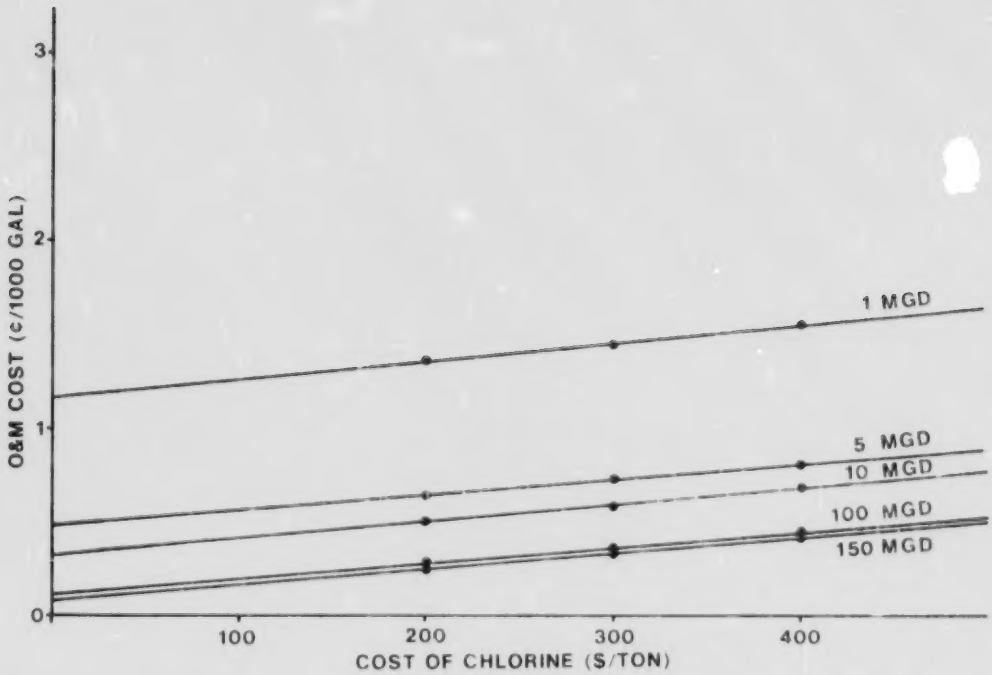

FIGURE 3. O&M COST FOR CHLORINATION SYSTEMS VERSUS COST OF CHLORINE

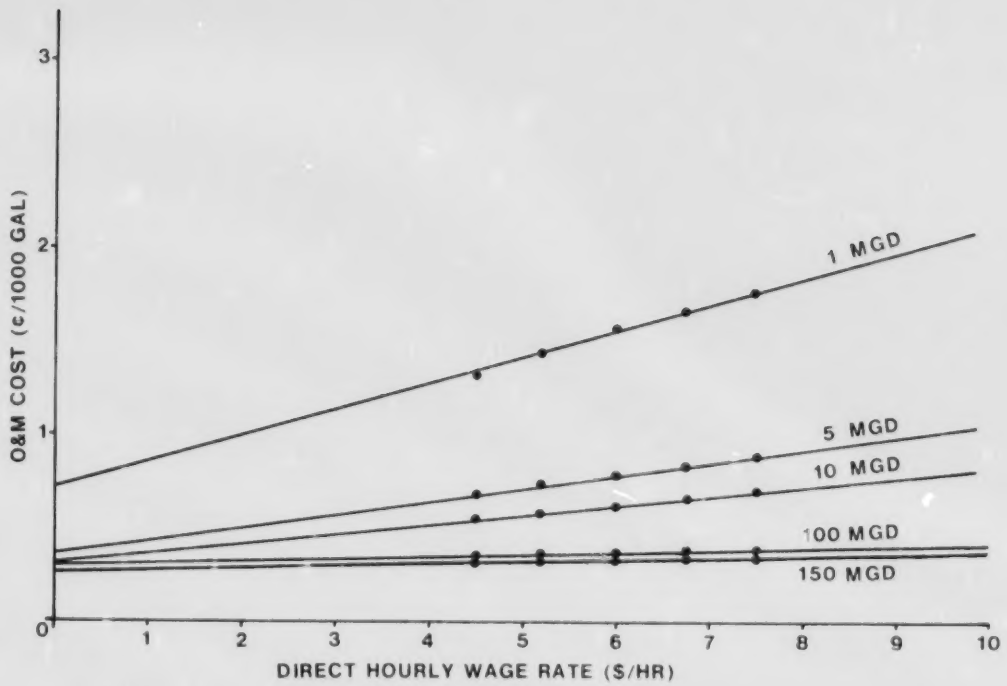

FIGURE 4. O&M COST FOR CHLORINATION SYSTEMS VERSUS DIRECT HOURLY WAGE RATE

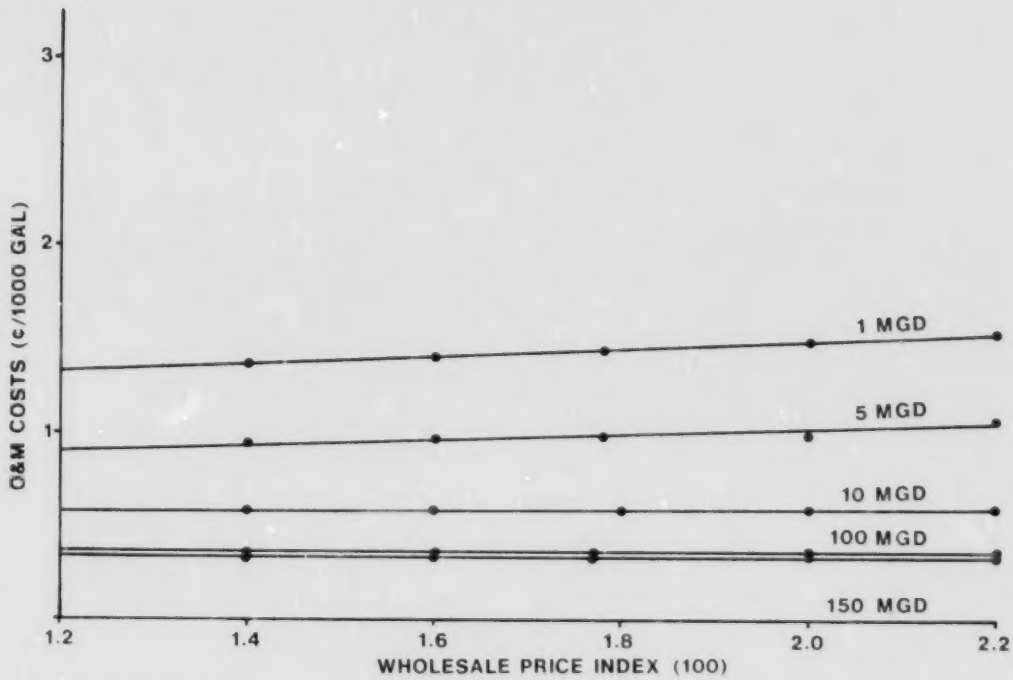

FIGURE 5. O&M COST FOR CHLORINATION SYSTEM VERSUS WHOLESALE PRICE INDEX

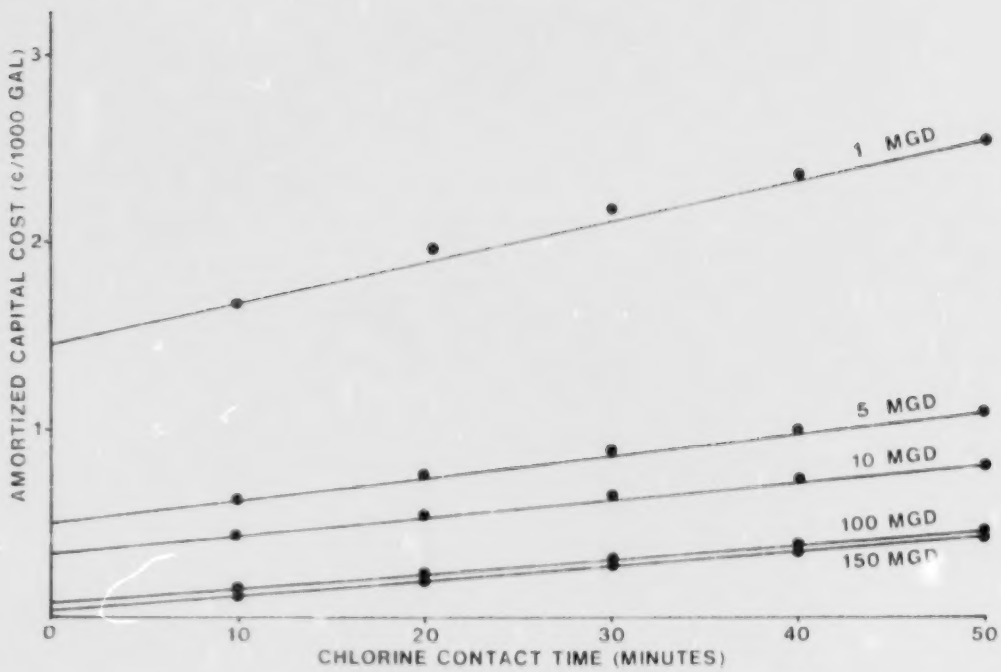

FIGURE 6. AMORTIZED CAPITAL COST FOR CHLORINATION SYSTEMS VERSUS CHLORINE CONTACT TIME

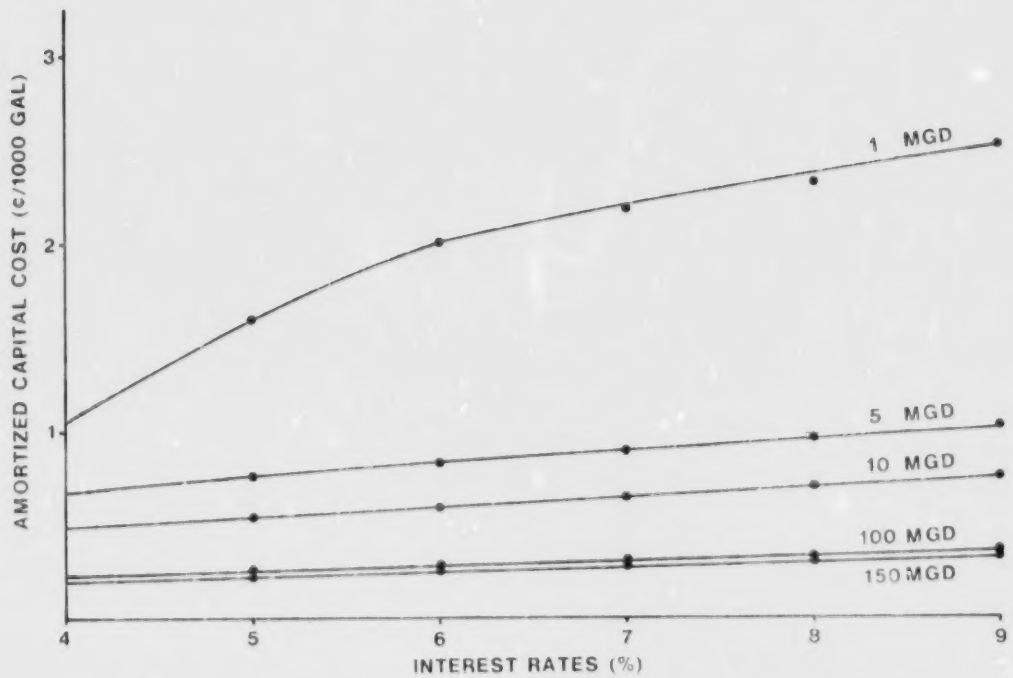

FIGURE 7. AMORTIZED CAPITAL COST FOR CHLORINATION SYSTEMS VERSUS INTEREST RATE

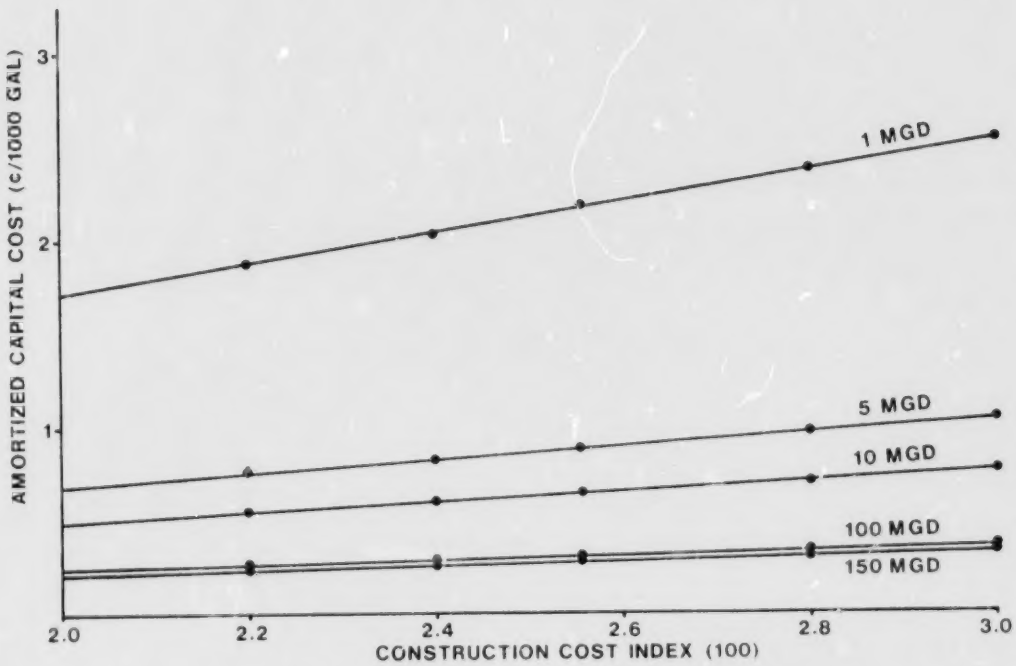

FIGURE 8. AMORTIZED CAPITAL COST FOR CHLORINATION SYSTEMS VERSUS CONSTRUCTION COST INDEX

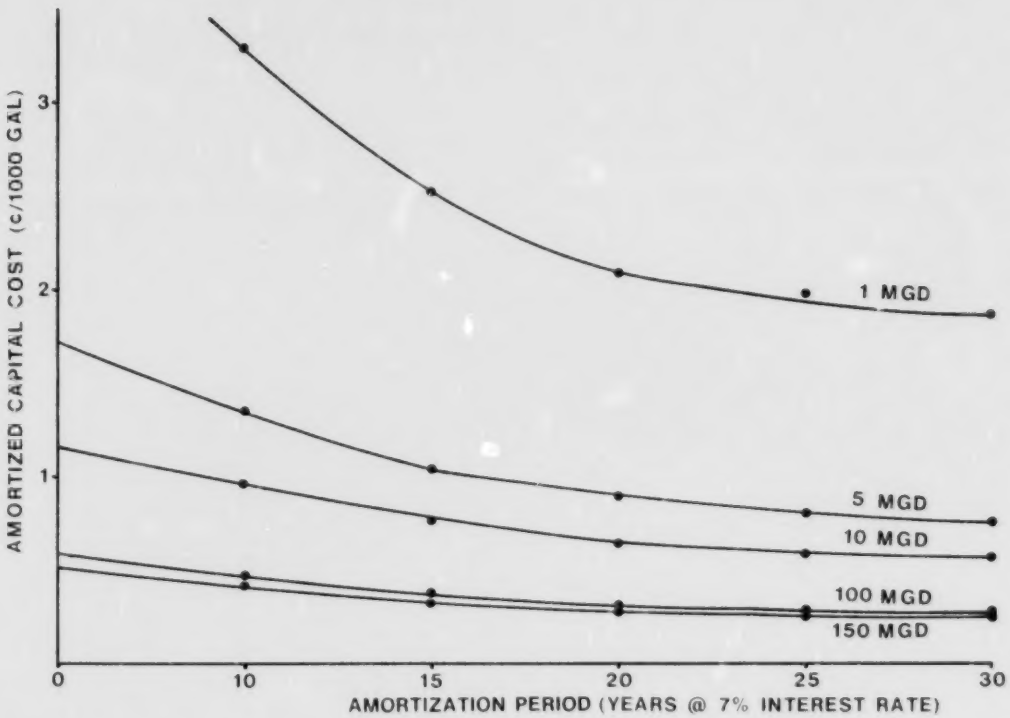

FIGURE 9. AMORTIZED CAPITAL COST FOR CHLORINATION SYSTEMS VERSUS AMORTIZATION PERIOD

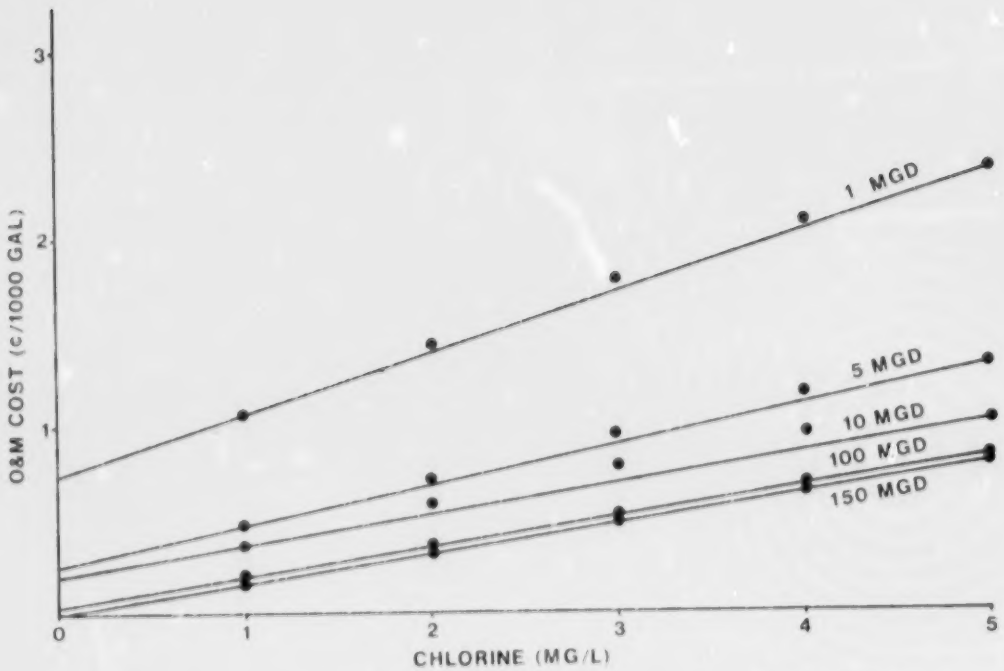

FIGURE 10. O&M COST FOR CHLORINATION SYSTEMS VERSUS CHLORINE DOSAGE

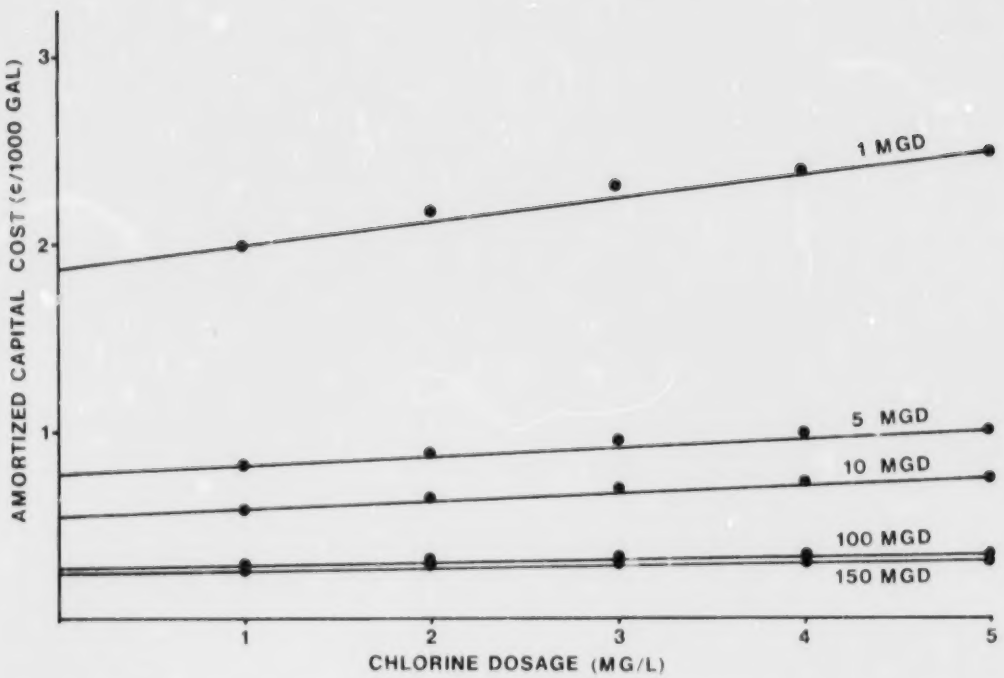

FIGURE 11. AMORTIZED CAPITAL COSTS FOR CHLORINATION SYSTEMS VERSUS CHLORINE DOSAGE

TABLE 2. CHLORINE COSTS ASSUMING STANDARDIZED DESIGN LEVELS

(c/1000 gal)

Item	1 mgd			5 mgd			10 mgd			100 mgd			150 mgd		
	Capital	O & M	Total	Capital	O & M	Total	Capital	O & M	Total	Capital	O & M	Total	Capital	O & M	Total
Cl_2 Basin	.910	0.000	.910	.436	0.000	.436	.328	0.000	.328	.169	0.000	.169	.160	0.000	.160
Cl_2 Feed System	1.142	1.024	2.167	.385	.546	.932	.255	.452	.707	.075	.315	.390	.062	.304	.366
Total Cost	2.053	1.024	3.077	.821	.546	1.368	.583	.452	1.035	.244	.315	.559	.222	.304	.526

$$2\ NaClO_2 + Cl_2 \rightarrow 2\ ClO_2 + 2\ NaCl \quad (1)$$

(181) (71) (135) (117)

1.3 mg/l 0.5 mg/l 0.9 mg/l 0.8 mg/l

Therefore, the chlorine feeding system and contact basins were estimated for a 0.5 mg/l dosage of chlorine with the rest of the standardized values fixed at the levels shown in Table 1. The cost of sodium chlorite was estimated as follows:

$NaClO_2$ cost (¢/1000 gal) = ($0.70/lb)(13.34 lb/mil gal)

= 0.934¢/1000 gal

The $NaClO_2$ cost was added to the cost of chlorine (0.5 mg/l) to yield the cost of a 1 mg/l dosage of ClO_2. These values are shown in Table 3 for 1, 5, 10, 100, and 150 mgd plants. Figure 12 shows the cost of chlorine dioxide versus treatment plant capacity. All of the factors which influence the cost of ClO_2 disinfection with the exception of $NaClO_2$ cost, would be the same as those shown in the section on chlorination.

Figure 13 illustrates sensitivity in O & M cost due to changes in the cost of $NaClO_2$. Amortized Capital cost sensitivity would be estimated by examining the effect of changing the Cl_2 dosage.

As can be seen, chlorine dioxide is more expensive than chlorination but has one advantage in that it can be generated with relative ease in a system with an existing chlorine feeding system. The only additional cost for such an operation would be to the incremental cost for sodium chlorite, although there are other mechanisms for generating chlorine dioxide, such as by the use of sodium chlorate, a process commonly used in the pulp and paper industry. None of these alternative methods are considered here because all of these systems have been built on a scale much too large for municipal water supply usage.

COST OF OZONATION

Another disinfectant which will be considered is ozone, although ozonation does not produce a disinfectant residual to be carried throughout the distribution system. Further, the reaction of ozone with organic matter occurring in water is not known. For purposes of this analysis, the design parameters listed in Table 4 have been assumed as standardized and a sensitivity evaluation of the cost of ozonation based on these parameters has been made for 1, 5, 10, 100, and 150 mgd plants operating at 70 percent capacity. As ozone can be produced from both air and oxygen, both systems are evaluated.

Cost of Ozone from Air

Figure 14 depicts the total unit cost for ozone generated by air versus plant capacity. The total unit costs are separated into O & M and Amortized Capital costs in Figure 15. The impact of the variables which affect O & M

TABLE 3. CHLORINE DIOXIDE COSTS ASSUMING STANDARDIZED DESIGN LEVELS

(c/1000 gal)

Item	1 mgd			5 mgd			10 mgd			100 mgd			150 mgd		
	Capital	O & M	Total	Capital	O & M	Total	Capital	O & M	Total	Capital	O & M	Total	Capital	O & M	Total
Cl_2 Basin	.911	0.000	.911	.436	0.000	.436	.328	0.000	.328	.170	0.000	.170	.160	0.000	.160
Cl_2 Feed System	.870	.577	1.448	.243	.231	.473	.150	.171	.323	.038	.093	.132	.031	.088	.119
$NaClO_2$ Cost	0.000	.933	.933	0.000	.933	.933	0.000	.933	.933	0.000	.933	.933	0.000	.933	.933
Total Cost	1.781	1.510	3.291	.679	1.164	1.842	.479	1.106	1.585	.208	1.027	1.585	.191	1.021	1.212

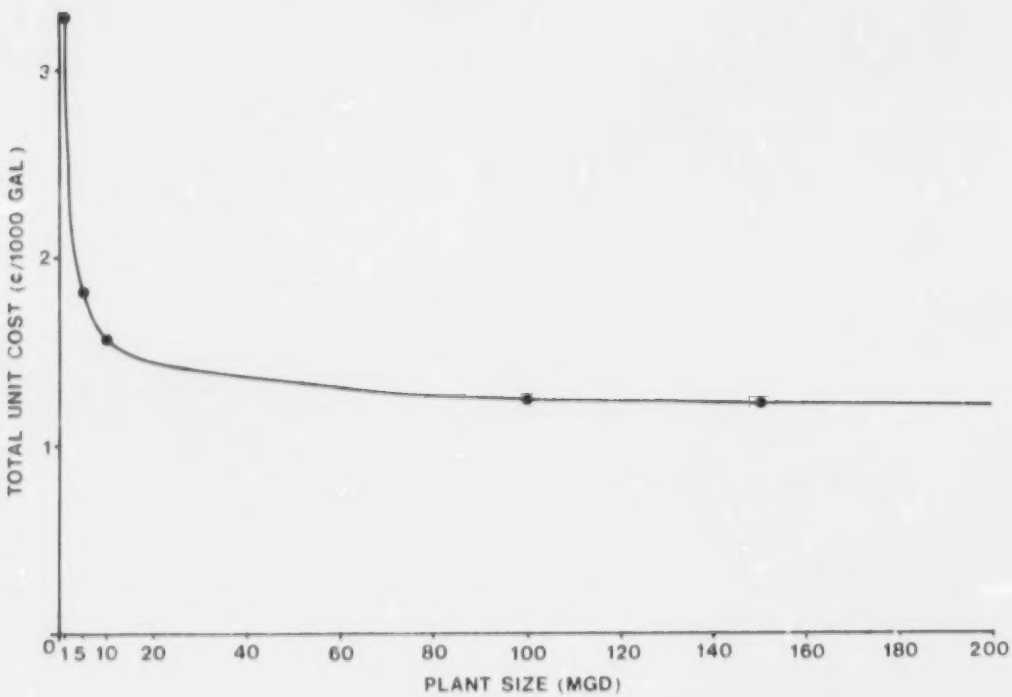

FIGURE 12. TOTAL UNIT COST FOR CHLORINE DIOXIDE VERSUS PLANT SIZE

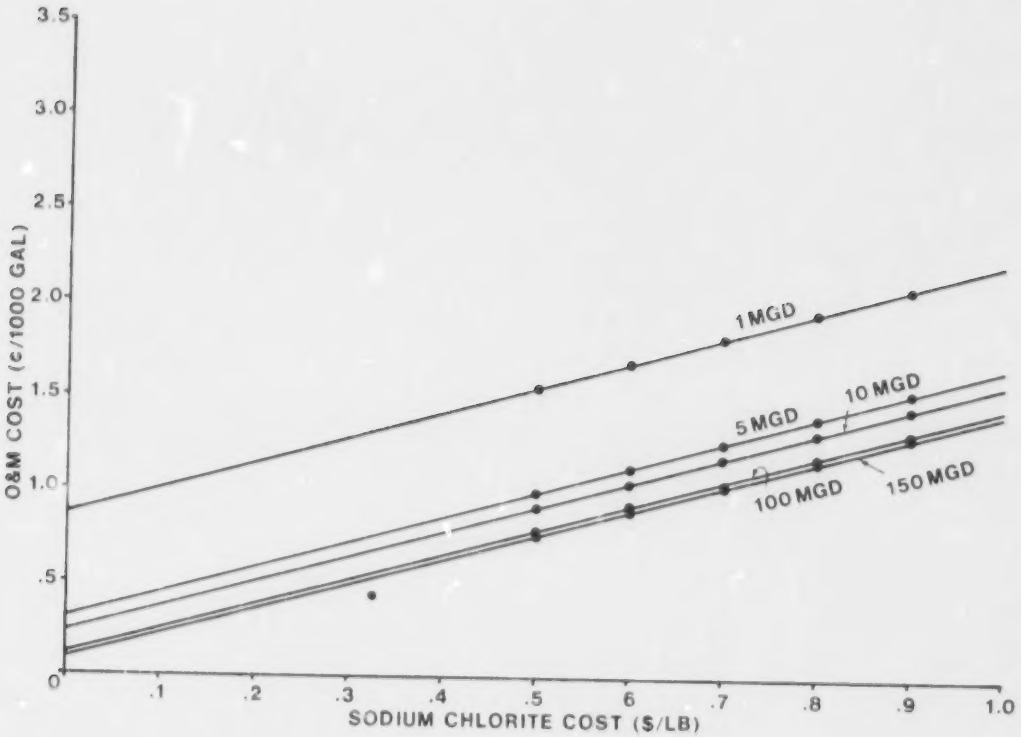

FIGURE 13. O&M COST FOR CHLORINE DIOXIDE SYSTEM VERSUS COST OF SODIUM CHLORITE

TABLE 4. DESIGN PARAMETERS FOR OZONATION

Design Parameters (Variable)	Level
Ozone Dose	1 mg/l
Ozone Contact Time	20 min
Cost of Oxygen	0.046 $/lb
Construction Cost Index	256.7
Wholesale Price Index	178.1
Direct Hourly Wage Rate	5.19 $/hr
Amortization Interest Rate	7 percent
Amortization Period	20 yr
Electric Power Cost	$0.01/KWH
Design Parameter (Fixed)	
Capacity Factor	70 percent

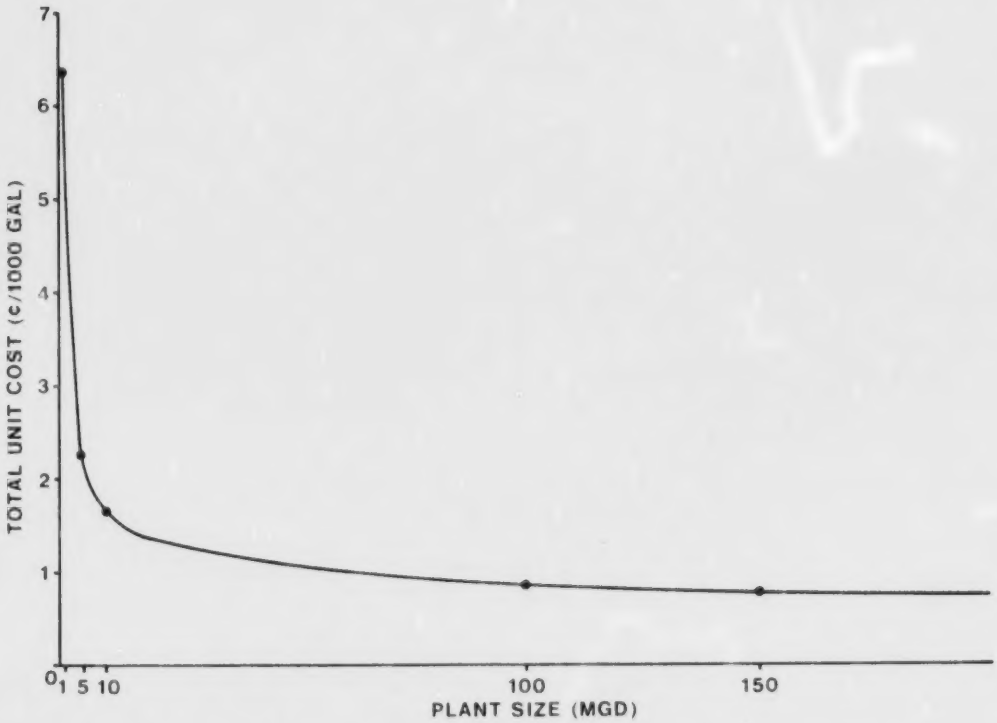

FIGURE 14. TOTAL UNIT COSTS FOR OZONATION (AIR) VERSUS PLANT SIZE

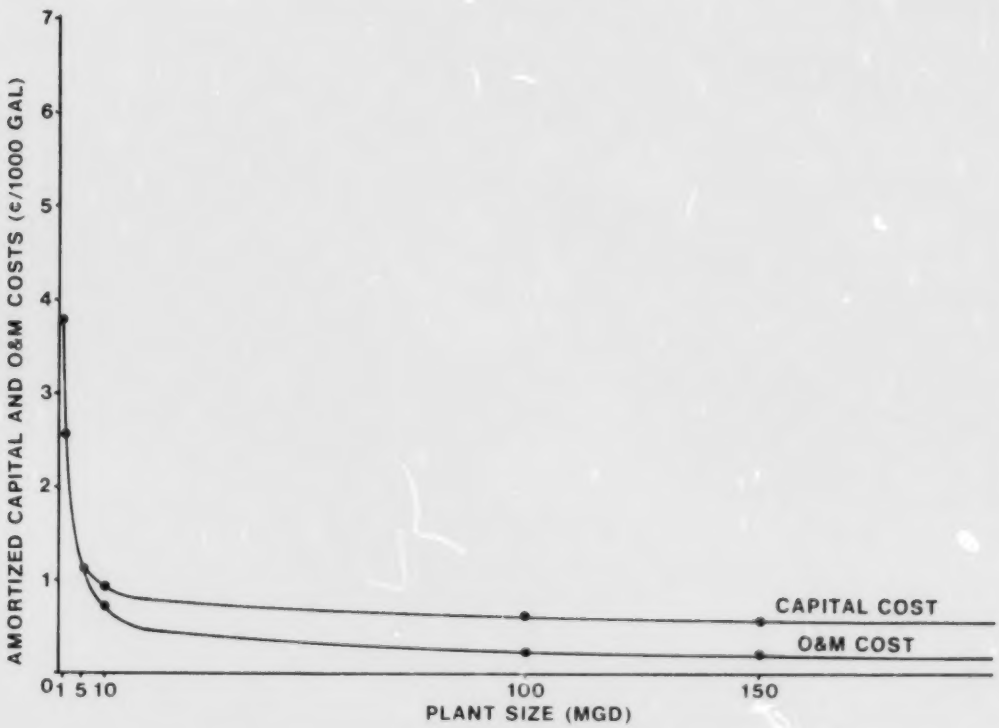

FIGURE 15. AMORTIZED CAPITAL AND O&M COSTS FOR OZONATION (AIR) VERSUS PLANT SIZE

cost are shown in Figures 16 through 18. These variables are as follows: direct hourly wage rate, wholesale price index, and cost of electric power in kilowatt hours.

Figures 19 through 22 illustrate the sensitivity of capital costs to the following variables: ozone contact time, construction cost index, and interest rate and amortization period. Ozone dose, as can be seen from Figures 23 and 24, affects both Amortized Capital and O & M costs.

Table 5 summarizes the costs for 1, 5, 10, 100, and 150 mgd plants based on standardized levels of the design variables in Table 4.

Cost of Ozone from Oxygen

Ozone can also be generated by using oxygen. Figures 25 and 26 show the total unit costs and the disaggregated costs (O & M and Amortized Capital), respectively, versus plant capacity. Figures 27 and 28 illustrate the sensitivity of the cost of ozonation (O & M and Amortized Capital costs) to the cost of liquid oxygen.

Table 6 summarizes the costs of 1, 5, 10, 100, and 150 mgd plants using the standardized variables in Table 4.

COST OF AERATION

Aeration is frequently practiced for the removal of hydrogen sulfide and reduced materials, such as ferrous iron and manganous manganese. In the laboratory, aeration or purging is used as an analytic procedure to remove trihalomethanes from water and it might therefore be used successfully as a treatment technique. Experimentation has shown, however, that at typical air-to-water ratios used in water treatment for removal of taste- and odor-causing compounds (1:1) little removal of chloroform takes place. For this analysis it was therefore assumed that the air-to-water ratio of 30 cu ft of air to 1 cu ft of water would provide adequate removal of trihalomethanes, which is consistent with laboratory results for effective chloroform removal. Table 7 contains the standardized variables which were examined in the cost analysis.

Figure 29 is a typical capital cost curve for an aeration basis as a function of throughput in thousands of cubic feet. Figures 30 and 31 are O & M Amortized Capital cost curves, respectively, for the diffused aeration system based on thousands of standard cubic feet per minute of air. Table 8 contains the cost per thousand gallons for a 1, 5, 10, 100, and 150 mgd plant based on the standardized cost assumptions shown in Table 7.

COST OF GRANULAR ACTIVATED CARBON

Granular activated carbon (GAC) is not a substitute for chlorine disinfection, but is well suited for the removal of various types of dissolved organic materials including chloroform and other trihalomethanes. Most but not all dissolved organics can be adsorbed, which actually removes them from solution.[11] Fresh, granular carbon has the following advantages for water

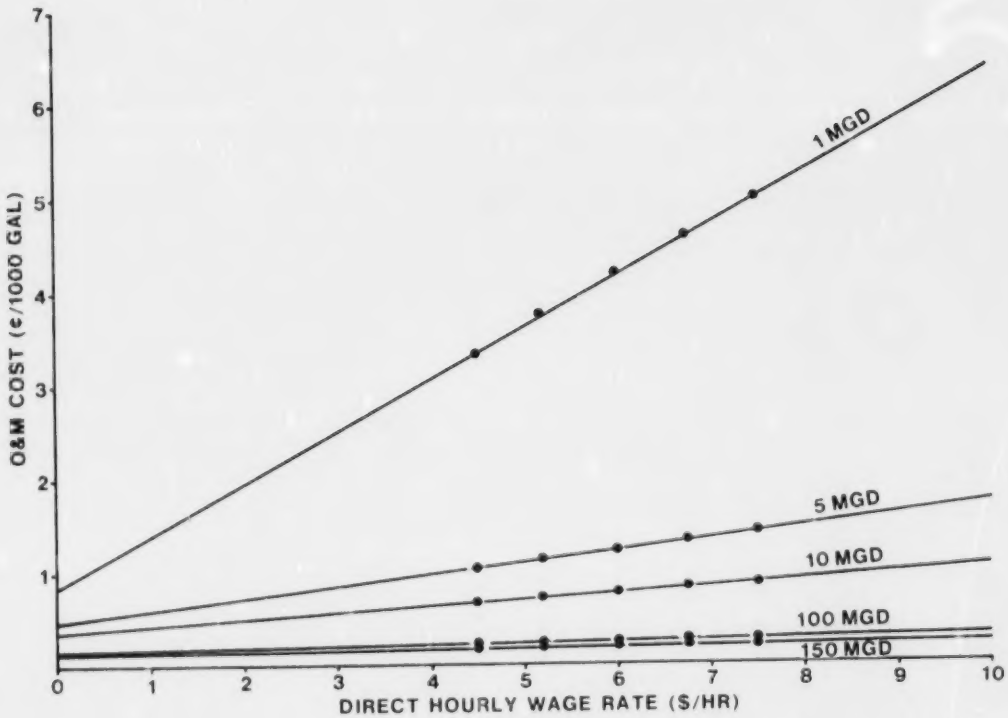

FIGURE 16. O&M COSTS FOR OZONATION (AIR) VERSUS DIRECT HOURLY WAGE RATE

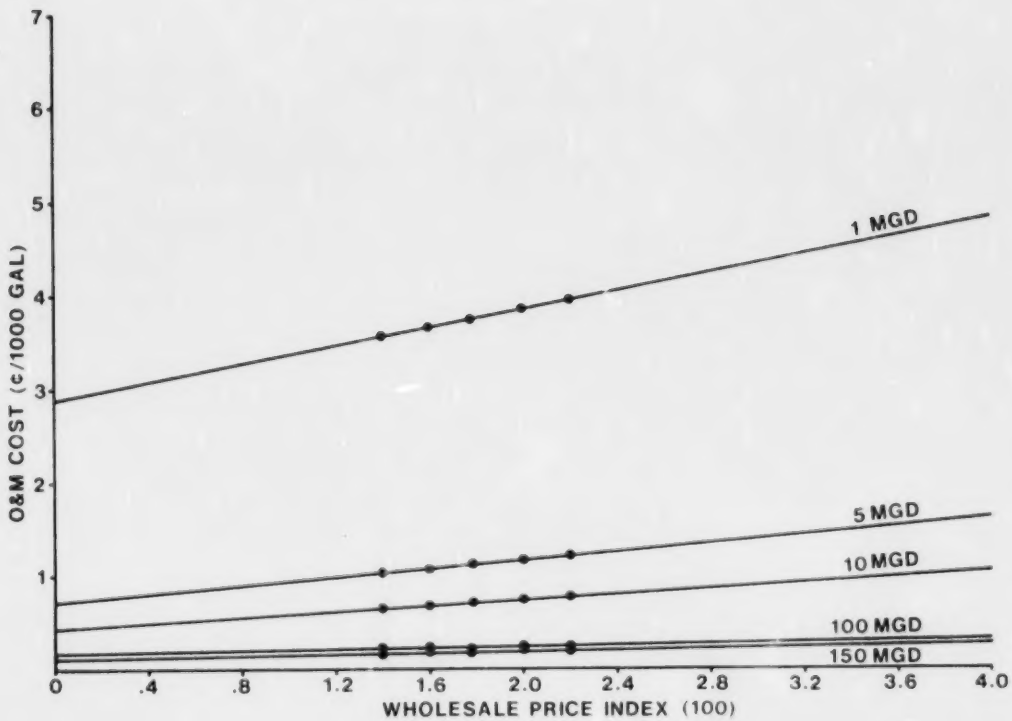

FIGURE 17. O&M COST FOR OZONATION (AIR) VERSUS WHOLESALE PRICE INDEX

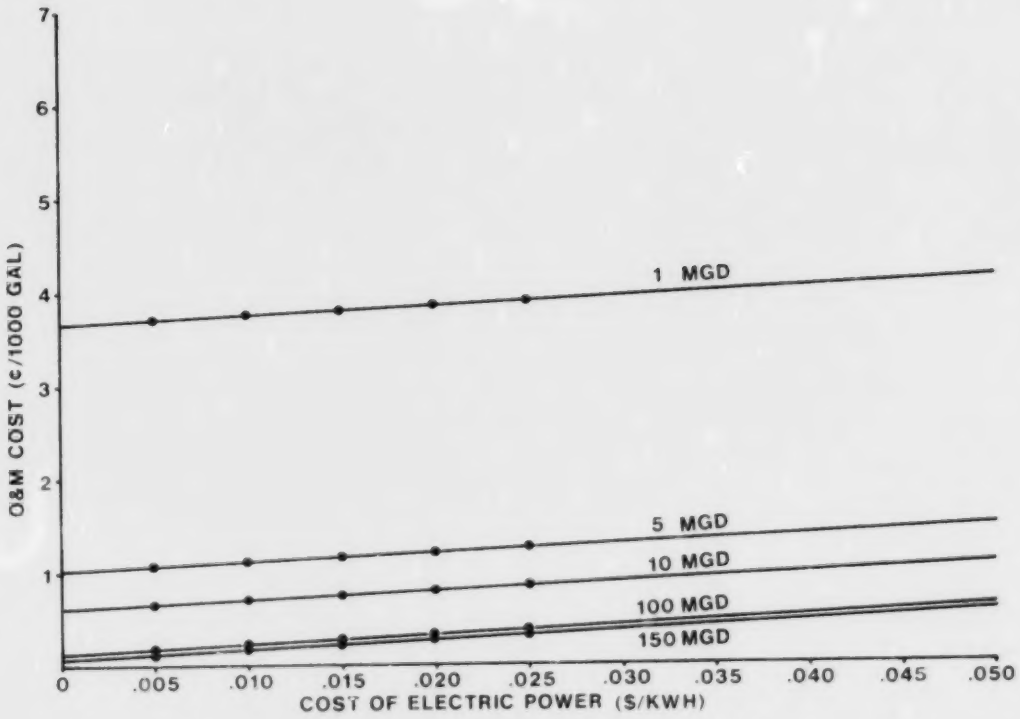

FIGURE 18. O&M COST FOR OZONATION (AIR) VERSUS ELECTRIC POWER COST

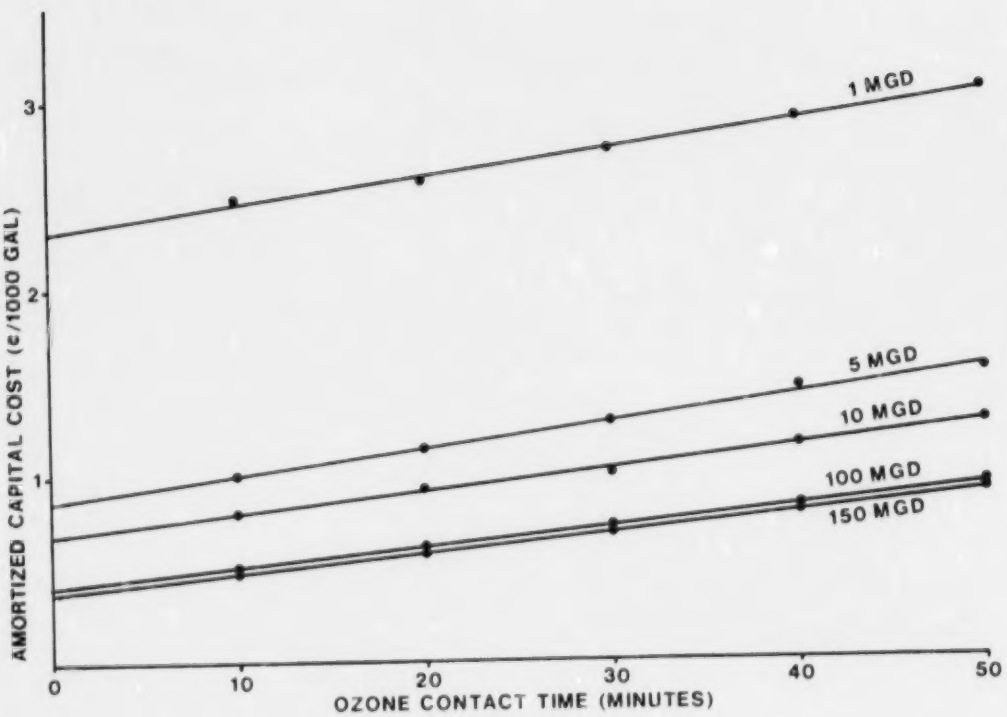

FIGURE 19. AMORTIZED CAPITAL COSTS FOR OZONATION (AIR) VERSUS OZONE CONTACT TIME

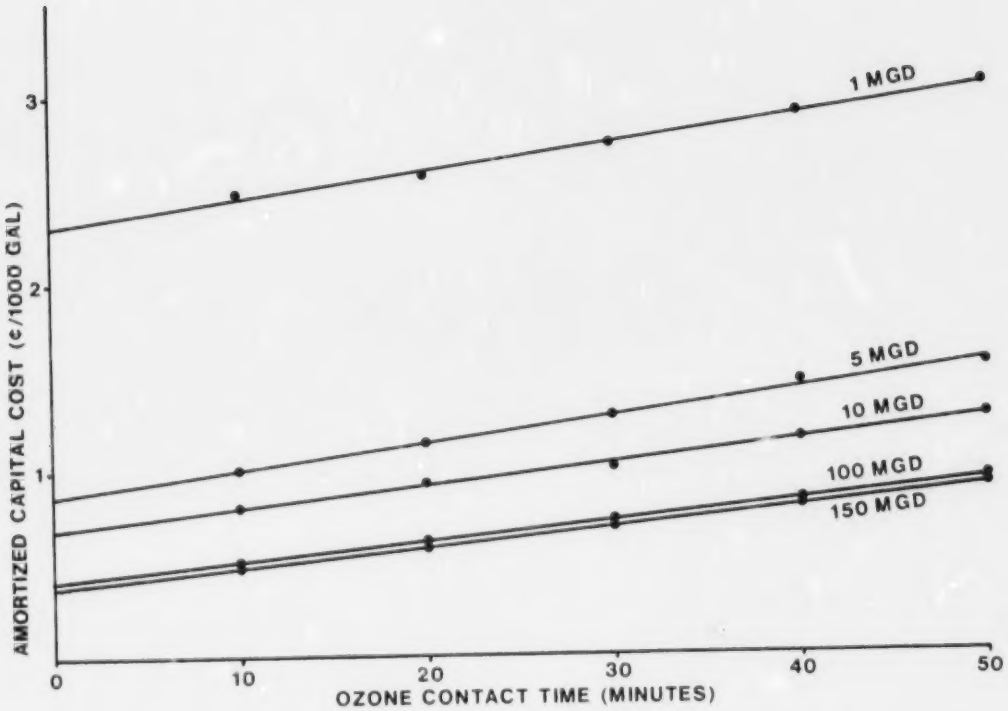

FIGURE 19. AMORTIZED CAPITAL COSTS FOR OZONATION (AIR) VERSUS OZONE CONTACT TIME

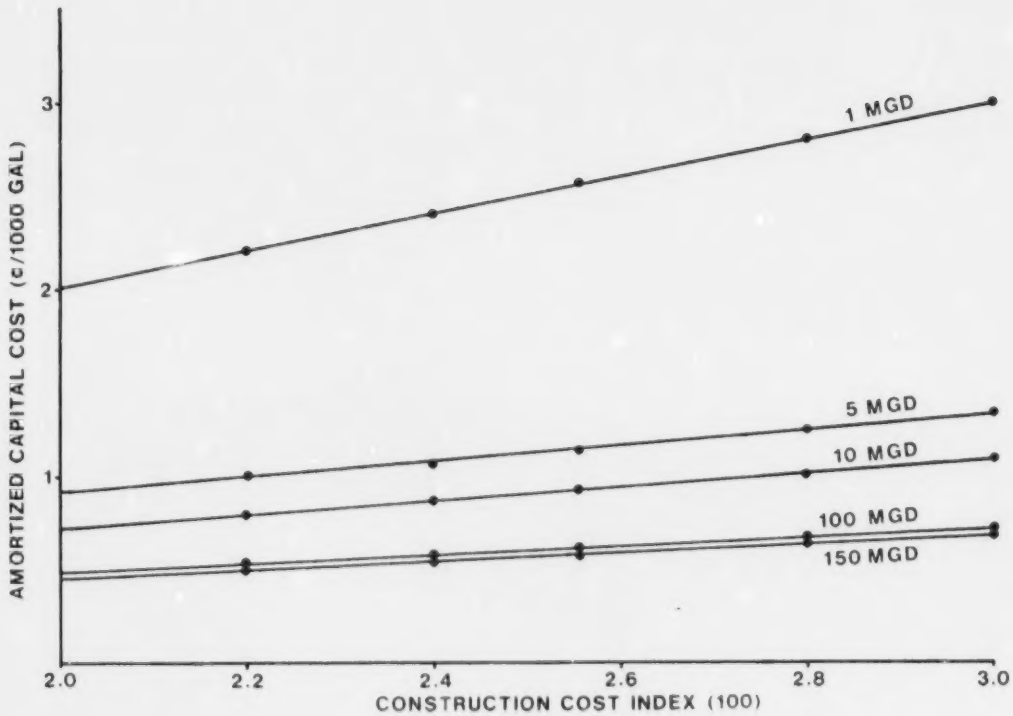

FIGURE 20. AMORTIZED CAPITAL COST FOR OZONATION (AIR) VERSUS CONSTRUCTION COST INDEX

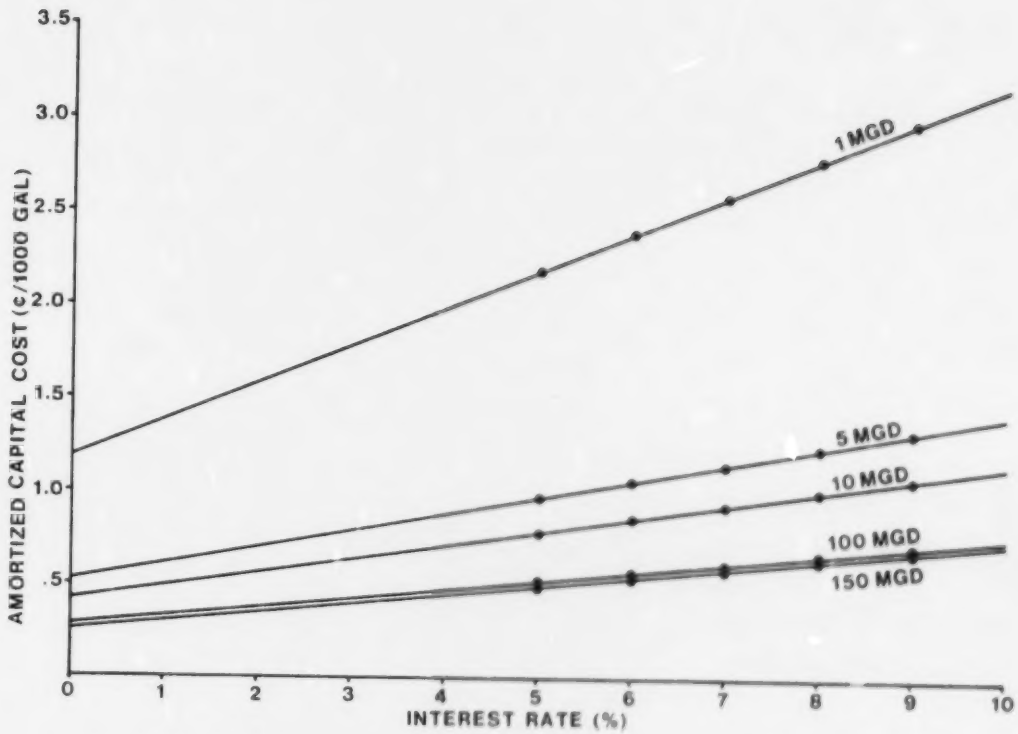

FIGURE 21. AMORTIZED CAPITAL COST FOR OZONATION (AIR) VERSUS INTEREST RATE

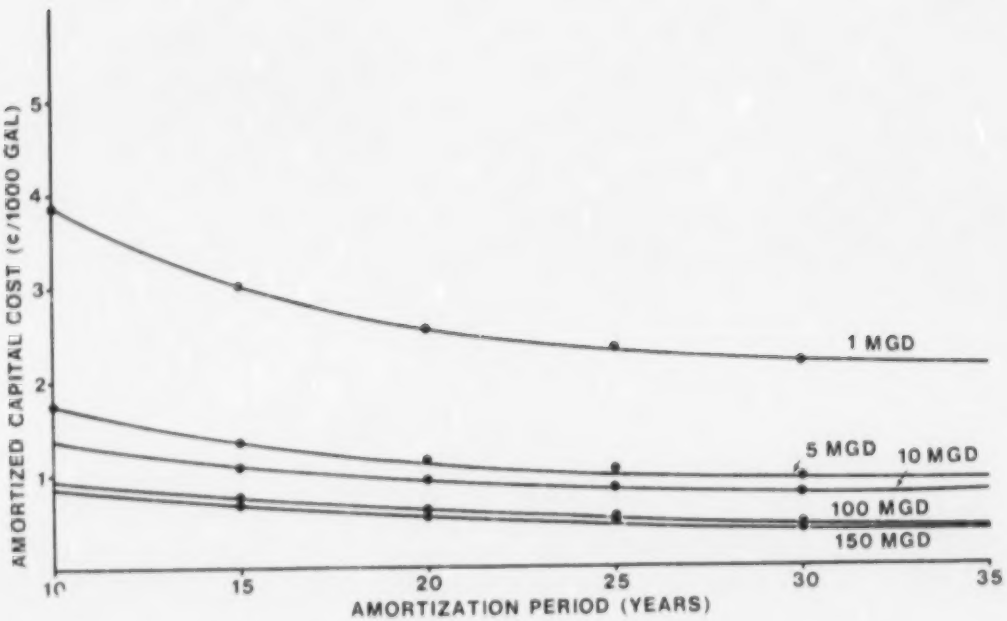

FIGURE 22. AMORTIZED CAPITAL COST FOR OZONATION (AIR) VERSUS AMORTIZATION PERIOD

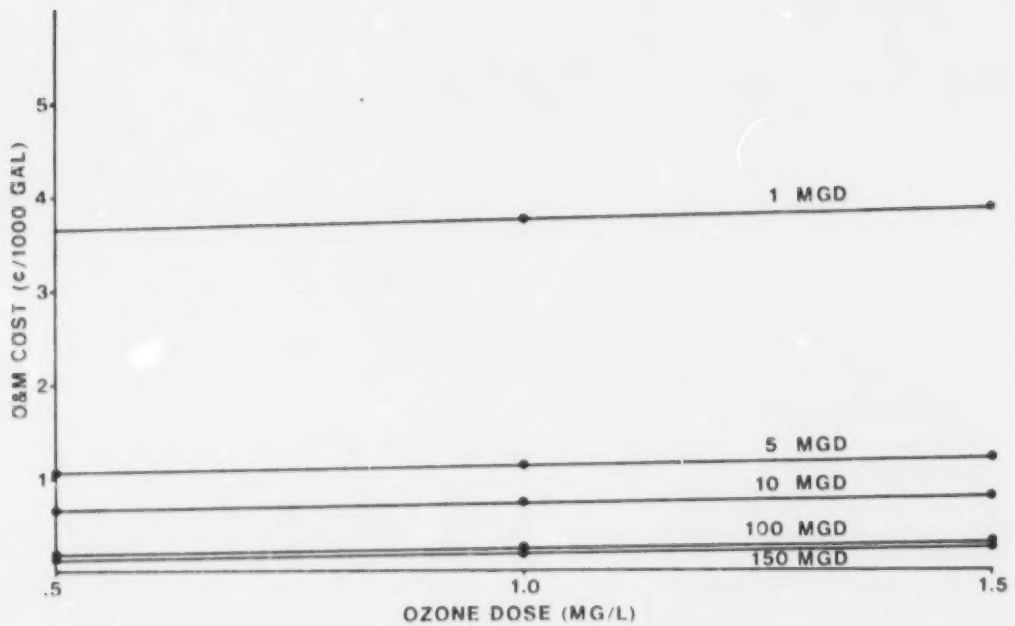

FIGURE 23. O&M COST FOR OZONATION (AIR) VERSUS OZONE DOSE

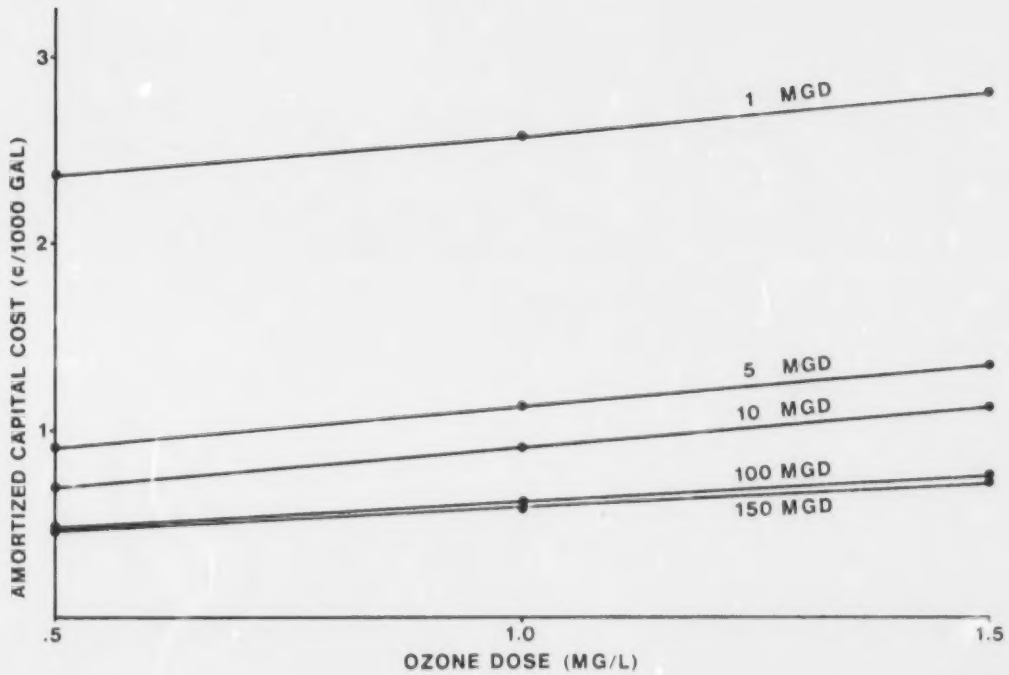

FIGURE 24. AMORTIZED CAPITAL COST FOR OZONATION (AIR) VERSUS OZONE DOSE

TABLE 5. OZONE (AIR) COSTS ASSUMING STANDARDIZED DESIGN LEVELS

(c/1000 gal)

Area	1 mgd			5 mgd			10 mgd			100 mgd			150 mgd		
	Capital	O & M	Total	Capital	O & M	Total	Capital	O & M	Total	Capital	O & M	Total	Capital	O & M	Total
Ozone Generating Facilities	.563	.091	0.654	.474	.091	.566	.440	.091	.532	.345	.091	.436	.330	.091	.422
Aeration Basin, Covers, Baffles	1.244	0.000	1.244	.486	0.000	.486	.372	0.000	.372	.236	0.000	.236	.229	0.000	.299
Diffused Air System	.769	3.672	4.441	.183	1.034	1.217	.112	.629	.741	.033	.145	.178	.028	.115	.143
O_2 Storage Tank	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total Cost	2.576	3.764	6.340	1.143	1.126	2.269	.924	.721	1.645	.613	.237	.850	.587	.206	.793

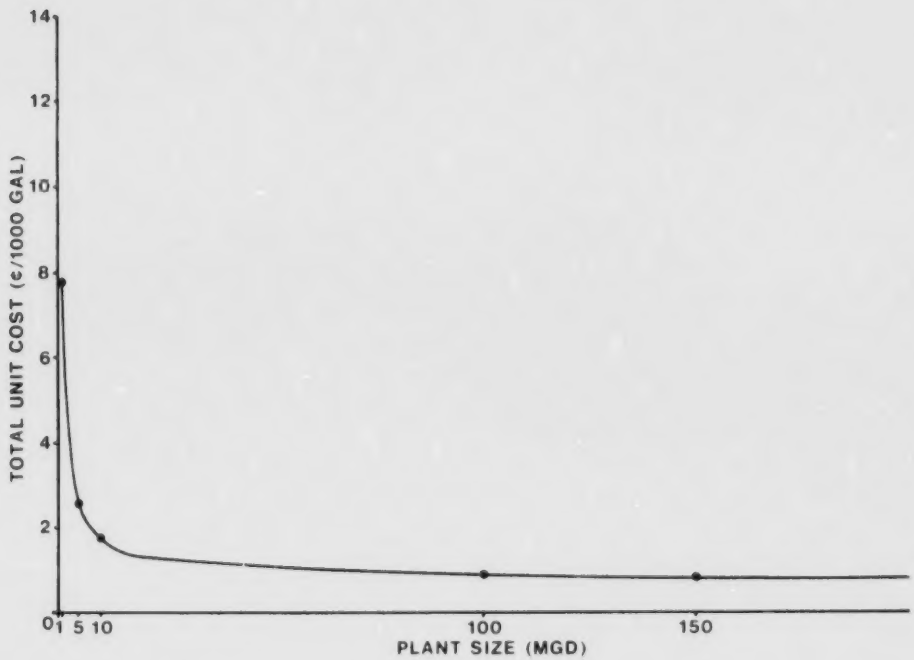

FIGURE 25. TOTAL UNIT COST OF OZONATION (OXYGEN) VERSUS PLANT SIZE

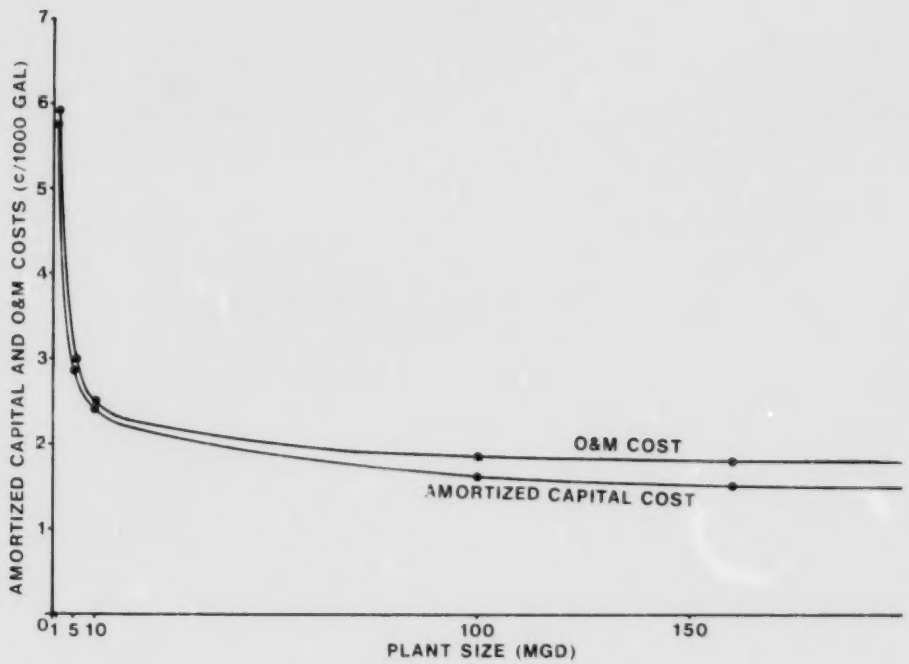

FIGURE 26. AMORTIZED CAPITAL AND O&M COSTS FOR OZONATION (OXYGEN) VERSUS PLANT SIZE

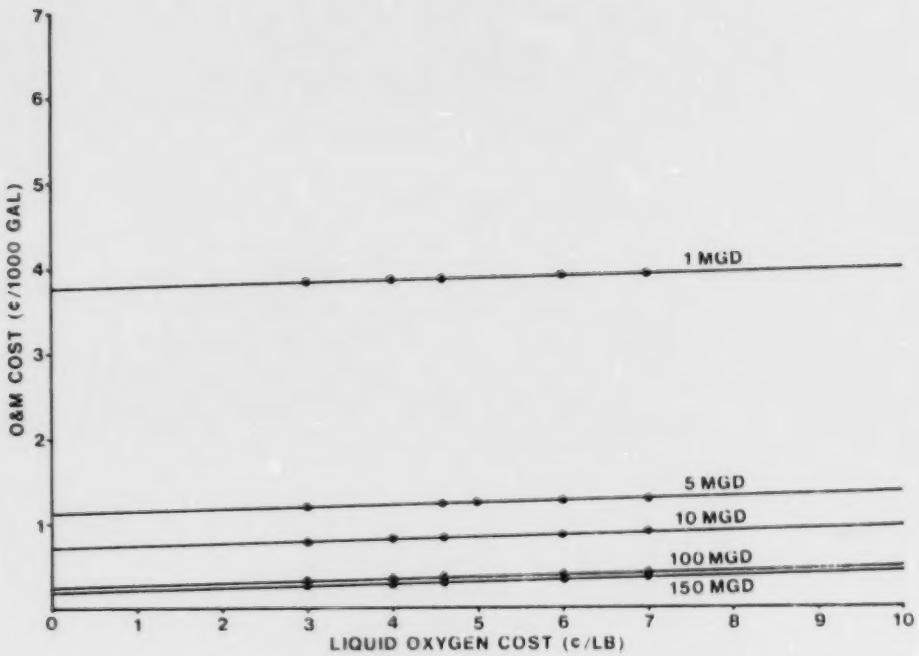

FIGURE 27. O&M COST FOR OZONATION (OXYGEN) VERSUS LIQUID OXYGEN COST

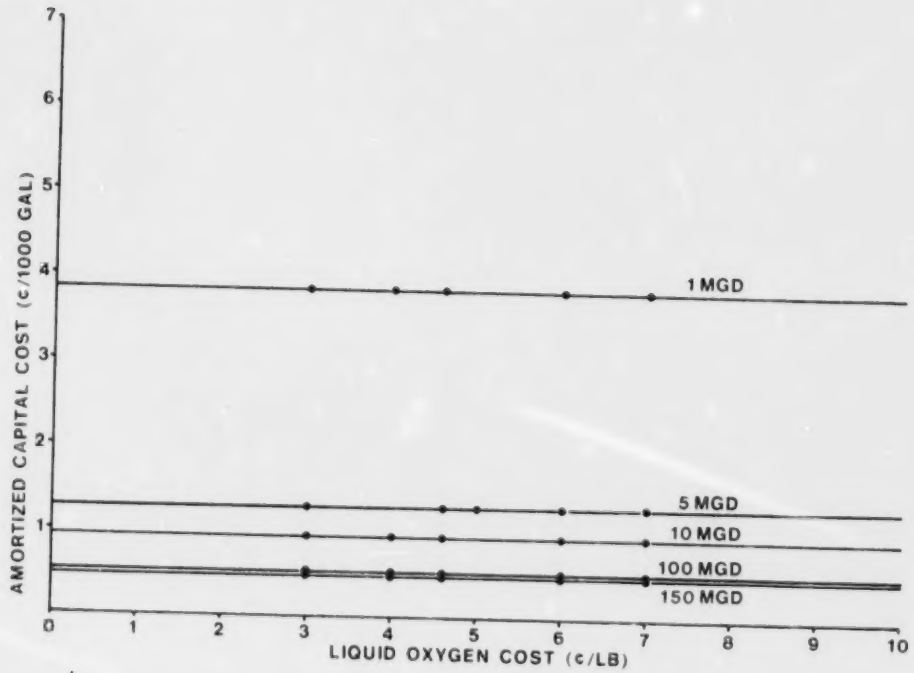

FIGURE 28. AMORTIZED CAPITAL COST FOR OZONATION (OXYGEN) VERSUS LIQUID OXYGEN COST

TABLE 6. OZONE (OXYGEN) COSTS ASSUMING STANDARDIZED DESIGN LEVELS

(c/1000 gal)

Item	1 mgd			5 mgd			10 mgd			100			150 mgd		
	Capital	O & M	Total	Capital	O & M	Total	Capital	O & M	Total	Capital	O & M	Total	Capital	O & M	Total
Ozone Generating Facilities	.303	.091	.395	.255	.091	.347	.237	.091	.328	.185	.091	.277	.178	.091	.269
Aeration Basin, Covers, Baffles	1.244	0.000	1.244	.486	0.000	.486	.372	0.000	.372	.236	0.000	.236	.229	0.000	.229
Diffused Air System	.769	3.672	4.441	.183	1.034	1.217	.112	.629	.741	.033	.145	.178	.028	.115	.143
O_2 Storage Tank	1.528	.075	1.603	.364	.115	.479	.216	.115	.331	.064	.115	.180	.056	.115	.171
Total Cost	3.844	3.839	7.683	1.288	1.241	2.529	.937	.835	1.772	.519	.352	.870	.491	.321	.812

TABLE 7. DESIGN PARAMETERS FOR AERATION

Design Parameters (Variable)	Level
Air to Water Ratio	30 cu ft: 1 cu ft
Contact Time	20 min
Construction Cost Index	256.7
Wholesale Price Index	178.1
Direct Hourly Wage Rate	5.19 $/hr
Amortization Interest Rate	7 percent
Amortization Period	20 yr
Electric Power Cost	$0.01/KWH
Design Parameter (Fixed)	
Capacity Factor	70 percent

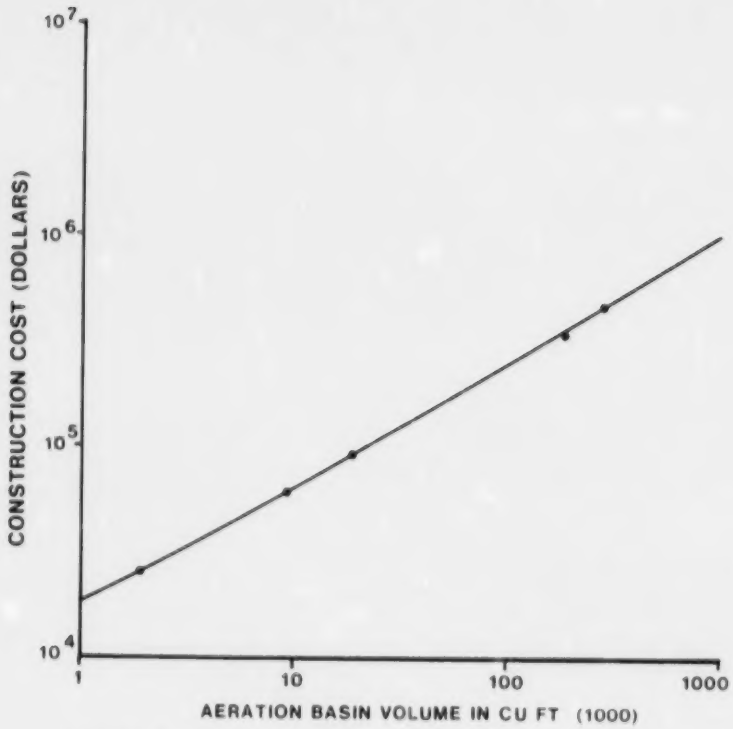

FIGURE 29. CONSTRUCTION COST FOR AN AERATION BASIN VERSUS VOLUME OF BASIN

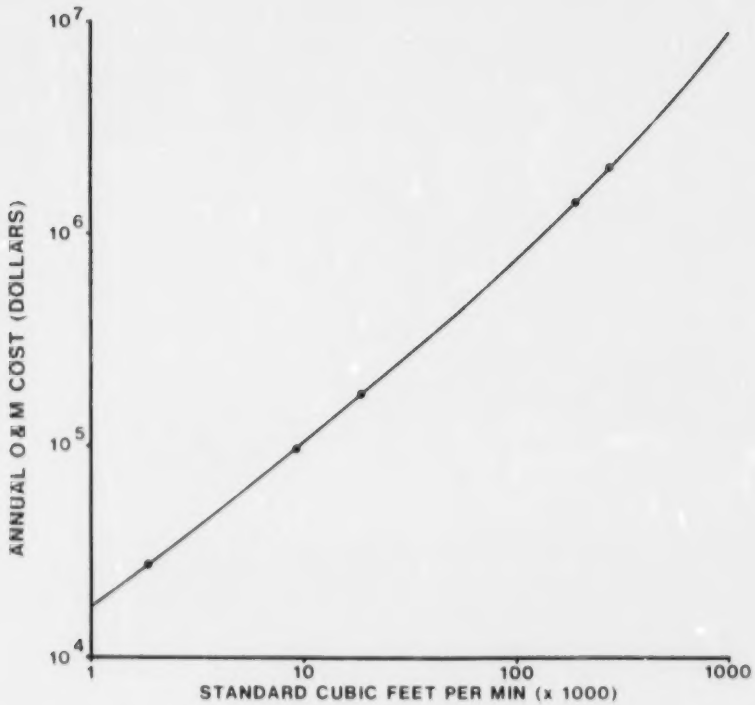

FIGURE 30. ANNUAL O&M COSTS FOR AIR SUPPLY VERSUS STANDARD CUBIC FEET PER MINUTE THROUGHPUT

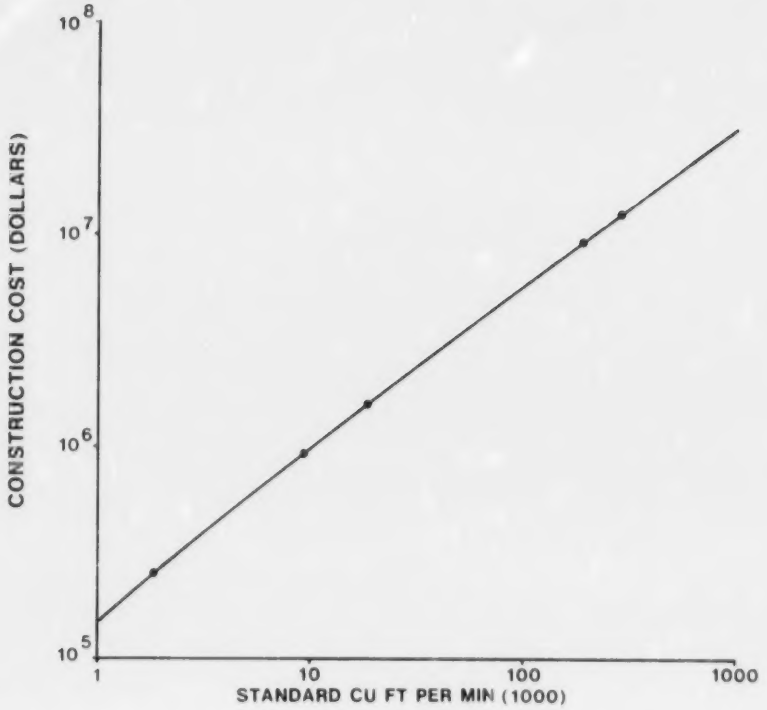

FIGURE 31 CONSTRUCTION COST FOR AIR SUPPLY VERSUS STANDARD CUBIC FEET PER MINUTE THROUGHPUT

TABLE 8. AERATION COSTS ASSUMING STANDARDIZED DESIGN LEVELS

(¢/1000 gal)

Item	1 mgd			5 mgd			10 mgd			100 mgd			150		
	Capital	O & M	Total	Capital	O & M	Total	Capital	O & M	Total	Capital	O & M	Total	Capital	O & M	Total
Aeration Basin	.958	0.000	.958	.436	0.000	.436	.334	0.000	.334	.167	0.000	.167	.151	0.000	.151
Air Supply	10.598	10.725	21.323	6.801	7.393	14.194	5.755	6.666	12.421	3.394	5.416	8.809	3.078	5.307	8.384
Total Cost	11.556	10.725	22.280	7.237	7.393	14.630	6.088	6.666	12.755	3.561	5.416	8.977	3.229	5.307	8.535

treatment:

a. Adsorption of trihalomethanes that have been formed by chlorination practiced prior to GAC treatment;

b. Adsorption of most trihalomethane precursors so that chlorination can be practiced after treatment with GAC without forming significant quantities of trihalomethanes;

c. Reduction of possibility of producing hitherto unknown organic byproducts during disinfection by reducing the amount of organic matter available for reaction with any disinfectant; and

d. Reduction in the general level of organics, thereby increasing the likelihood of removal of raw water organic contaminants that may be of concern now or in the future.

Treating water with activated carbon involves two major and separate process operations: filtration and reactivation. The water comes in contact with the carbon by passing through a structure filled wither with carbon granules or with a carbon slurry. Impurities are removed from the water by adsorption when sufficient time is provided for this process. The structure can be either a water treatment filter shell, in which the filter media has been replaced with GAC or an independent carbon filtration system. The separate carbon filtration system usually consists of a number of columns or basins used as contactors that are connected to a reactivation system. The primary focus of this economic analysis will be on the use of GAC as a replacement for existing media in the filter shell. The economics of a separate contactor system will also be examined.

After a period of use, the carbon's adsorptive capacity is exhausted and it must then be taken out of service and reactivated by combustion of the organic adsorbate. Fresh carbon is routinely added to the system to replace that lost during hydraulic transport and reactivation. These losses include both attrition due to physical deterioration and burning during the reactivation process.

The approach taken in this analysis is first to evaluate the use of GAC with an on-site reactivation system assuming that the GAC will replace the media in the filter shell. Various levels of key design parameters will be established at standard levels with the intent of evaluating their effect on sensitivity of the cost of GAC systems. The "standard" system will consist as in the previous analysis of fixing a given set of design variables at predetermined levels. Secondly, an analysis will be made for the replacement of GAC in the filter shell but with off-site or regional reactivation. Finally, an evaluation will be made of the cost of a separate GAC contactor system with on-site reactivation.

The Cost of GAC as Filter Media Replacement

As mentioned previously, it was assumed that GAC would replace sand in existing filters, thereby eliminating the need to consider the cost of separate GAC contactors. For purposes of this analysis, a water treatment plant is assumed to consist of an integral number of 1 mgd filters. For example, a 10 mgd water treatment system is assumed to consist of ten 1 mgd filters each with the following dimensions: 18.5' x 18.5' x 2.5', yielding a total volume of 865 cu ft per filter.

The standard values and the design parameters chosen for examination are shown in Table 9. All analyses perform will be based on the effect of changing the design variables around these standard values.

Before examining sensitivities, the impact of three basic factors must be considered: economies of scale, load factor, and reactivation frequency. Figure 32 depicts the economies of scale associated with plant size for GAC systems of 1, 5, 10, 100, and 150 mgd capacity, assuming the design variables are held at the levels shown in Table 9. The unit cost for a 1 mgd plant is approximately 44¢/1000 gal while the unit cost of a 150 mgd plant is close to 5.5¢/1000 gal. The cost curve rises sharply between 10 and 5 mgd, jumping from 12¢/1000 gal to 15.5¢/1000 gal. Figure 33 shows O & M and Amortized Capital costs versus plant capacity.

Figure 34 depicts the cost for a 100 mgd plant, operating at a 70 percent capacity factor, with the period between reactivation varying between 0.5 and 18 months. At might be expected, lengthening the time between reactivation reduces the unit cost from 7.5¢/1000 gal at 0.5 months to 1.6¢/1000 gal at 18 months.

Figure 35 shows the interaction between capacity factor and reactivation frequency for a 100 mgd plant, in which it is assumed that the product of reactivation period and load factor is 1, and that as capacity factor decreases, the period between reactivations increases. For example, when capacity factor is 100 percent, the reactivation frequency is assumed to be one month, and when the capacity factor is 50 percent the reactivation frequency is assumed to be two months. It can be seen that increasing the time between reactivation periods reduces unit costs; however, this reduced cost is offset by a reduced load factor which increases the unit cost. The net effect is an increased cost from 5.3¢/1000 gal (100 percent load factor @ one reactivation per month) to 6.2¢/1000 gal (50 percent load factor @ one reactivation every two months).

Having established the impact of these three variables (load factor, reactivation frequency, and economies of scale), it is possible to examine the sensitivity of cost to changes in the design parameters in Table 9. Some of these variables influence only Operating and Maintenance cost, some only Amortized Capital cost, and some of these variables affect both O & M and Amortized Capital cost. The first group of variables to be examined that influence O & M cost are as follows: hourly wage rate ($/hr), carbon loss

TABLE 9. DESIGN PARAMETERS FOR GRANULAR ACTIVATED CARBON

Design Parameters (Variable)	Level
Carbon Cost	0.38¢/lb
Carbon Loss per Reactivation Cycle	10 percent
Fuel Cost	1.26 $/mil BTU
Electrical Power Cost	0.01¢/KWH
Construction Cost Index	256.7
Wholesale Price Index	178.1
Direct Hourly Wage Rate	5.19 $/hr
Amortization Rate	7 percent
Amortization Period	20 yr
Design Parameters (Fixed)	
Contact Time	4.5 min
Hydraulic Loading Rate	2 gal/min/sq ft
Volume per Filter (1 mgd)	865 cu ft
Capacity Factor	70 percent
Reactivation Frequency	1.4 months
Loss in Adsorptive Capacity During Reactivation	0

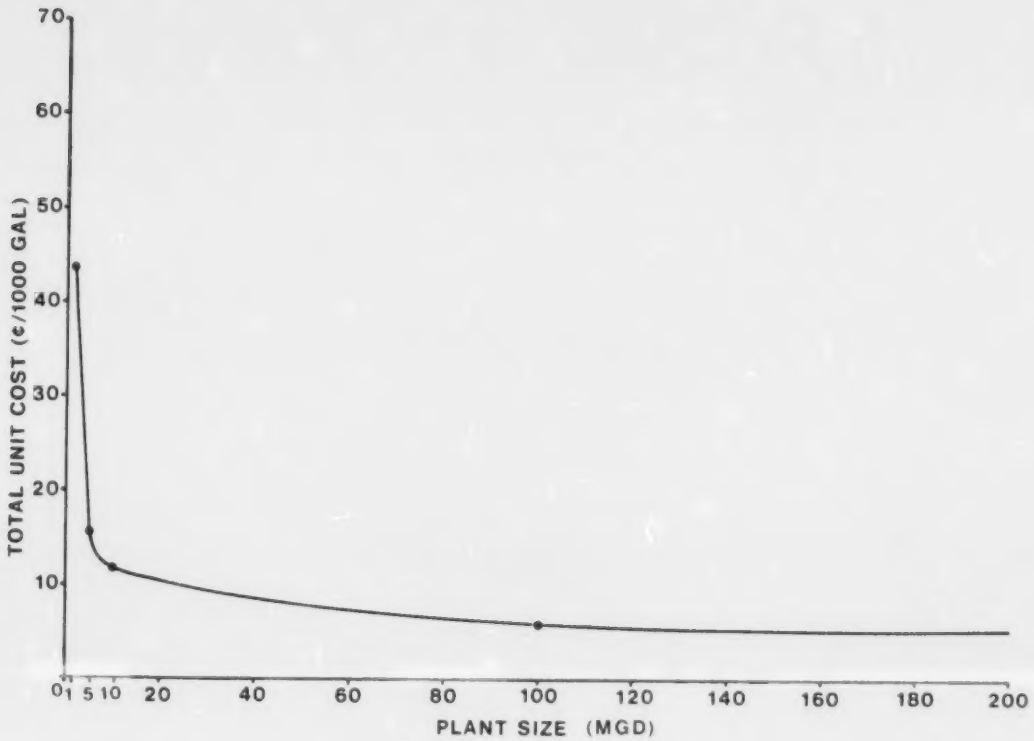

FIGURE 32. TOTAL UNIT COST VERSUS PLANT SIZE

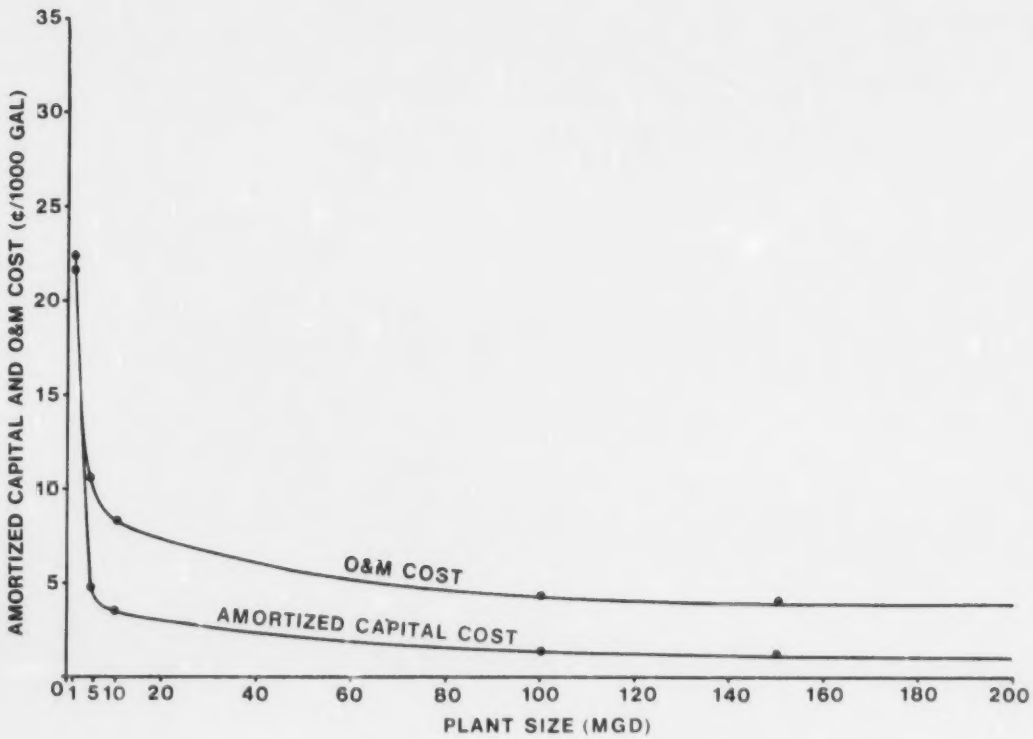

FIGURE 33. AMORTIZED CAPITAL AND O&M COSTS VERSUS PLANT SIZE

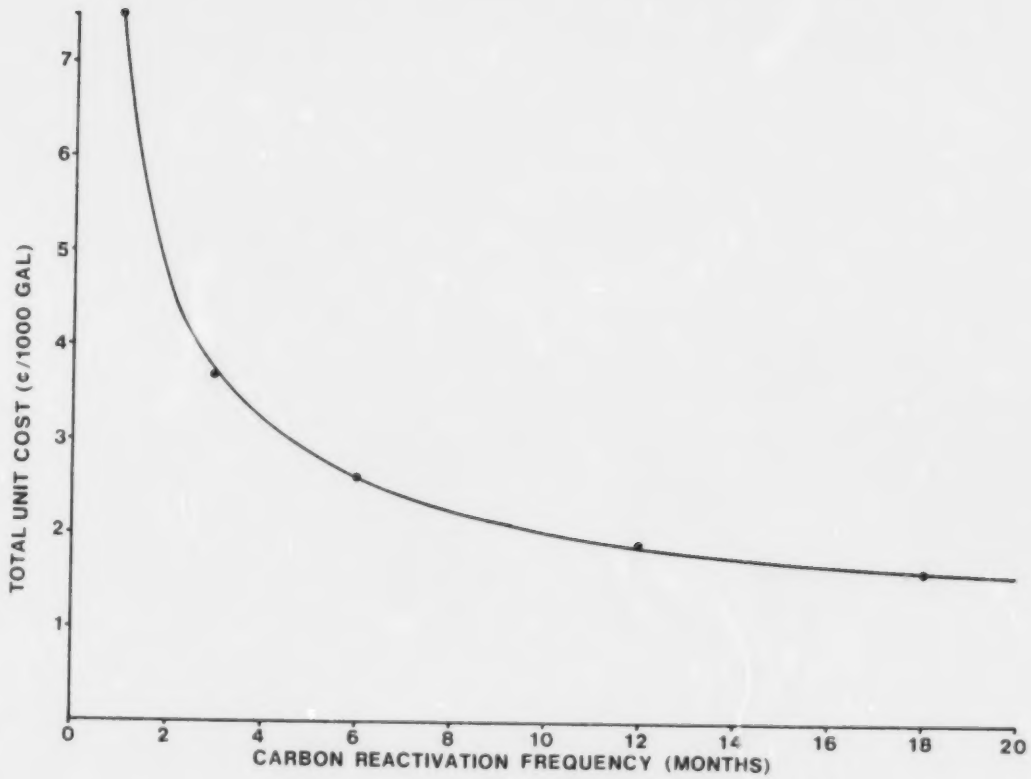

FIGURE 34. TOTAL UNIT COST FOR A 100 MGD PLANT VERSUS TIME BETWEEN REACTIVATIONS IN MONTHS

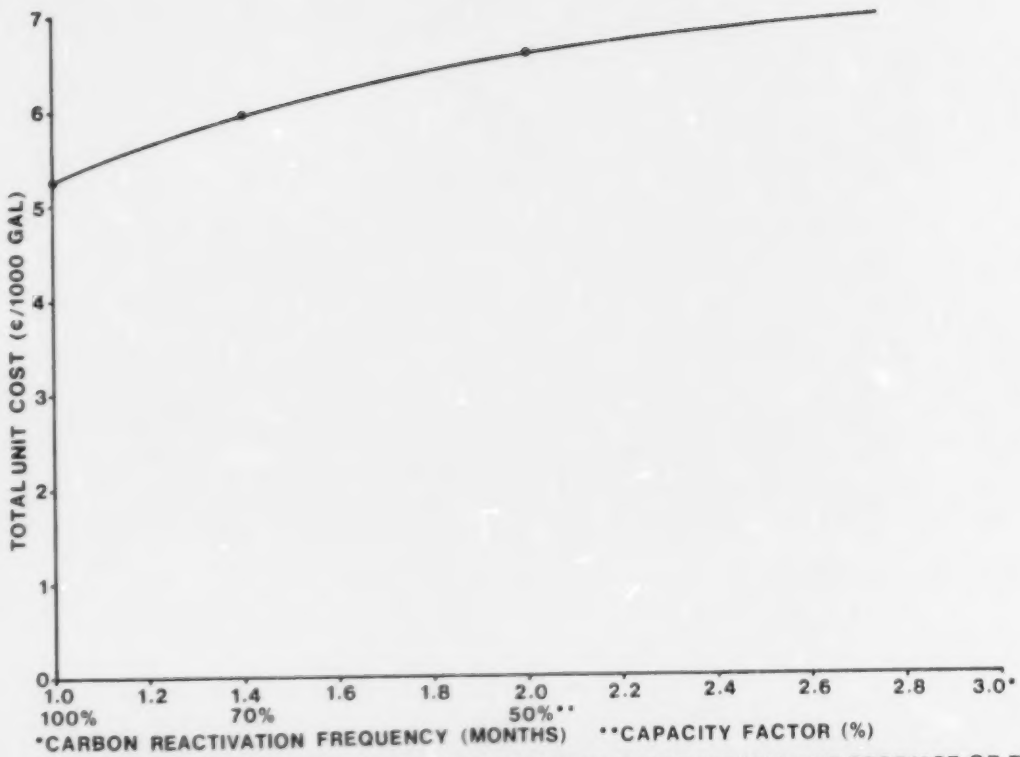

FIGURE 35. TOTAL UNIT COST FOR A 100 MGD PLANT VERSUS THE PRODUCT OF TIME BETWEEN REACTIVATIONS IN MONTHS AND CAPACITY FACTOR

per reactivation cycle, fuel cost, wholesale price index, and electrical power cost. Figures 36 through 40 illustrate the impact which these variables have on cost.

Figure 36 shows that changes in hourly wage rate have a greater impact on the cost of small plants than on large plants. For example, it can be seen that as the hourly rate increased from 5.19 $/hr to 7 $/hr, the O & M cost for 1 mgd plant increases from slightly over 21¢/1000 gal to slightly less than 28¢/1000 gal. The same wage rate increase in a 150 mgd plant increases the O & M cost from approximately 4¢/1000 gal to 4.5¢/1000 gal.

Figure 37 shows the changes in O & M costs which result from increases or decreases in carbon loss per reactivation cycle. Figures 37 through 40 show that O & M cost is very sensitive to changes in carbon loss but is somewhat less sensitive to changes in fuel cost, wholesale price index, and electric power cost.

The group of variables that influence Amortized Capital cost are as follows: Construction Cost Index (CCI), amortization interest rate, and amortization period in years. Figure 41 illustrates the variable impact that CCI has on Amortized Capital cost in ¢/1000 gal. The impact is great for small plants, but decreases for larger plants. Figure 42 illustrates the effects of increasing or decreasing interest rate on Amortized Capital cost. As with CCI, the effect of changing this parameter is greater for smaller plants than for larger plants. Figure 43 shows the same effect for changes in amortization period.

Several of the design parameters listed in Table 9 influence both Amortized Capital and O & M cost. These parameters are as follows: activated carbon cost, carbon reactivation frequency, and the interaction of carbon reactivation frequency and load factor. Figures 44 and 45 illustrate the influence that the cost of activated carbon will have on both Amortized Capital and O & M cost. Figures 46, 47, 48, and 49 show these same impacts for carbon reactivation frequency and for the interaction of carbon reactivation frequency and load factor.

To illustrate how the sensitivity analysis can be applied to the standard values in order to study the impact of local conditions on costs, the following example has been constructed. If it were assumed that all of the standardized values were held at the levels shown in Table 9, with the exception of activated carbon loss, it would be possible to estimate the impact that changes in its value would have on the system cost. Examining Figure 37, it can be seen that as compared to the standardized values when activated carbon loss is 15 percent for a 100 mgd plant the percent change in O & M cost is + 29.5 percent, but when it is at 5 percent, the change is - 14.7 percent. The standardized values yield an Amortized Capital cost of 1.5¢/1000 gal and an O & M cost of 4.5¢/1000 gal. Therefore, as carbon loss affects only O & M cost, the change in total cost would be as follows:

$$\text{GAC system cost (15 percent)} = 1.5 + [4.5 + 4.5\ (.295)] \quad (2)$$

$$= 7.3¢/1000 \text{ gal} \quad (3)$$

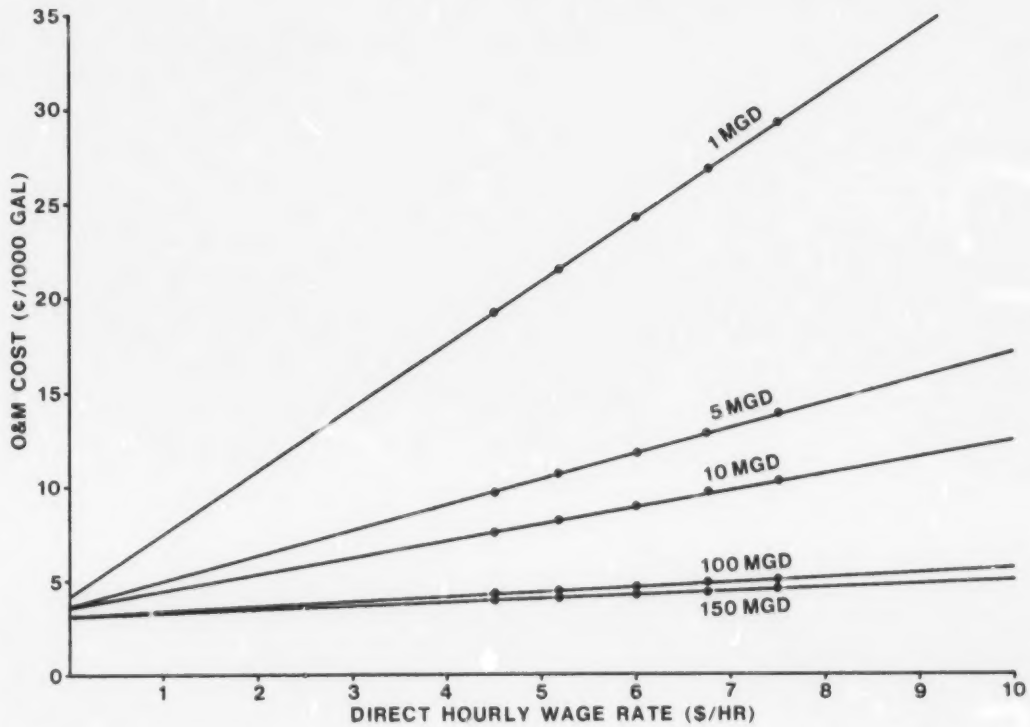

FIGURE 36. O&M COST VERSUS DIRECT HOURLY WAGE RATE

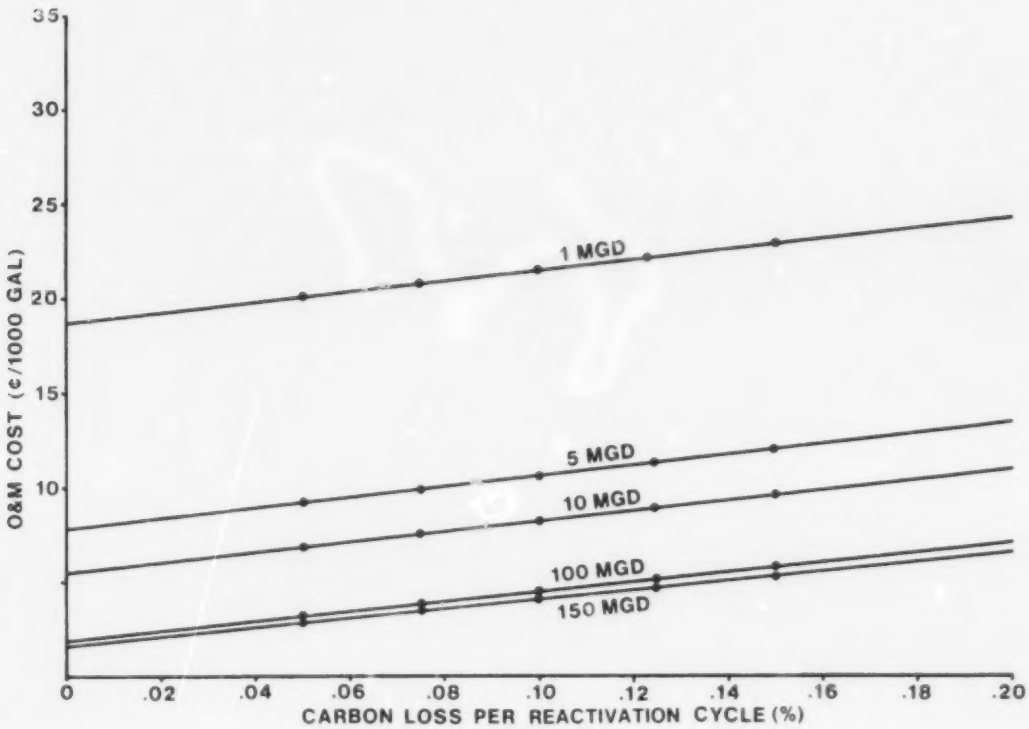

FIGURE 37. O&M COST VERSUS CARBON LOSS PER REACTIVATION CYCLE

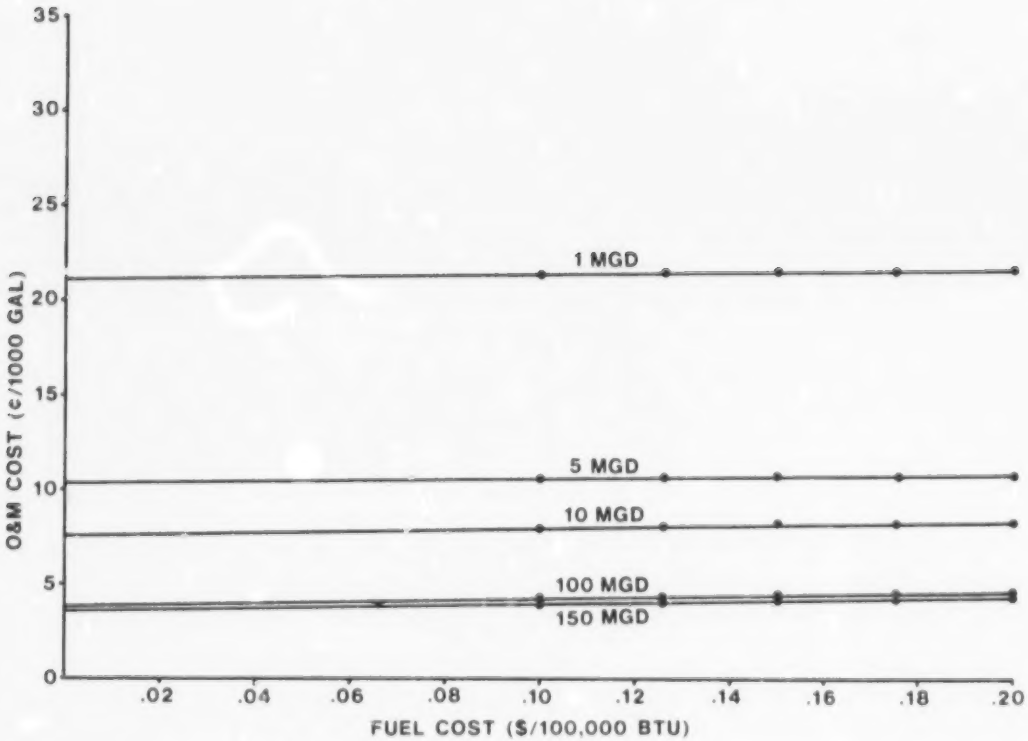

FIGURE 38. O&M COST VERSUS FUEL COST

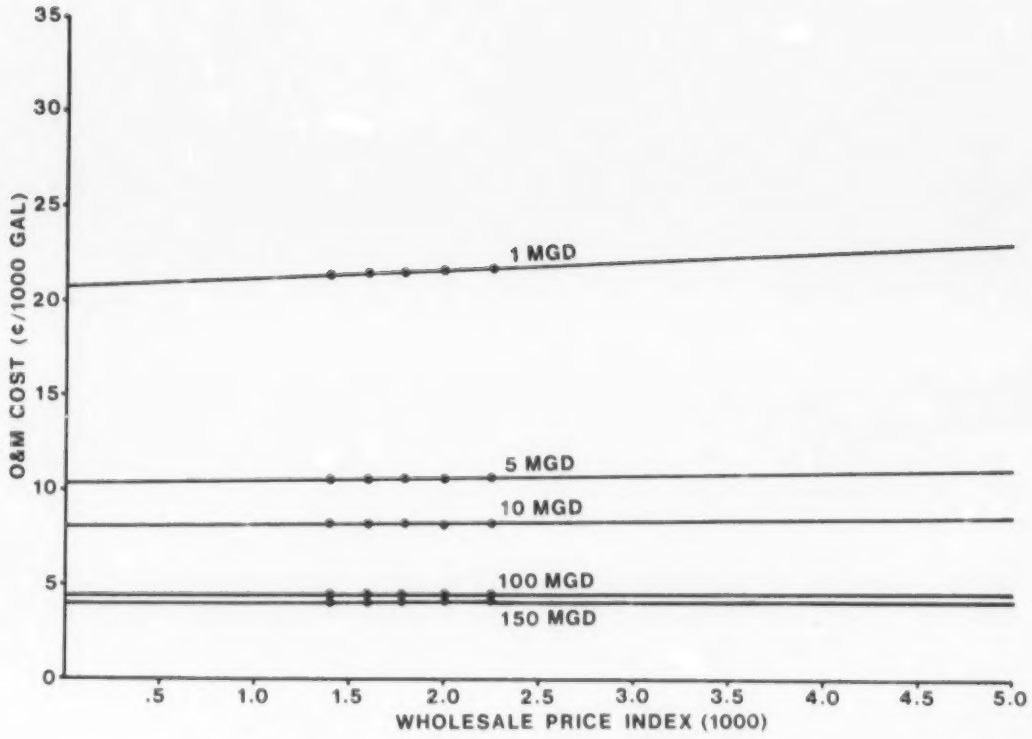

FIGURE 39. O&M COST VERSUS WHOLESALE PRICE INDEX

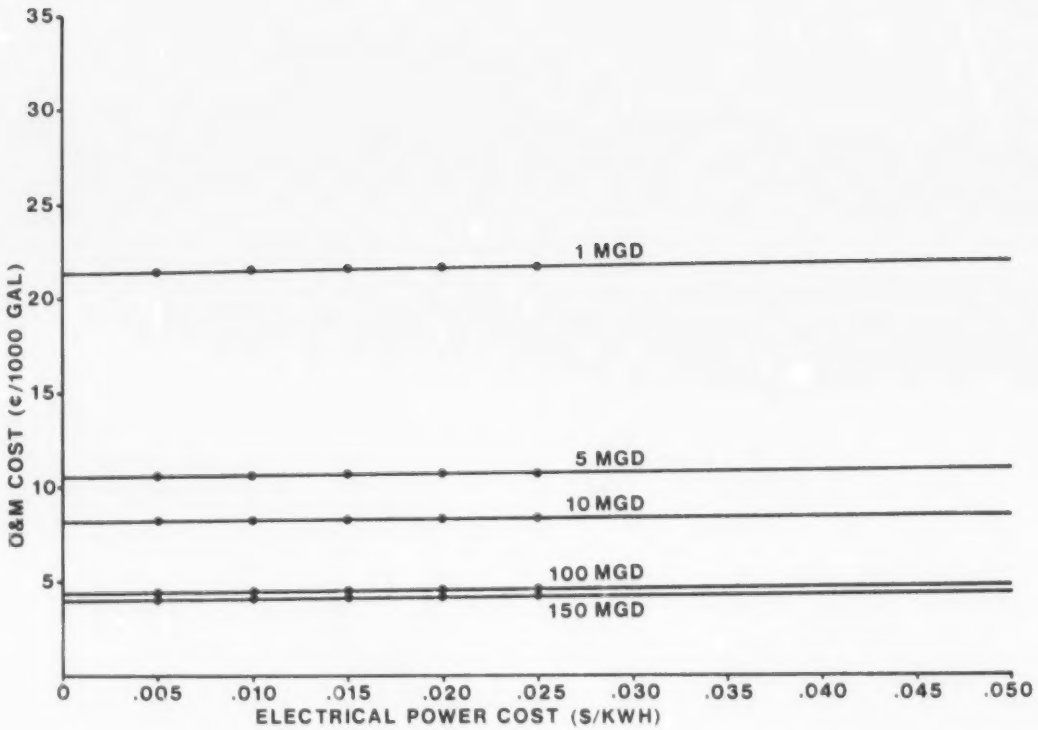

FIGURE 40. O&M COST VERSUS ELECTRICAL POWER COST

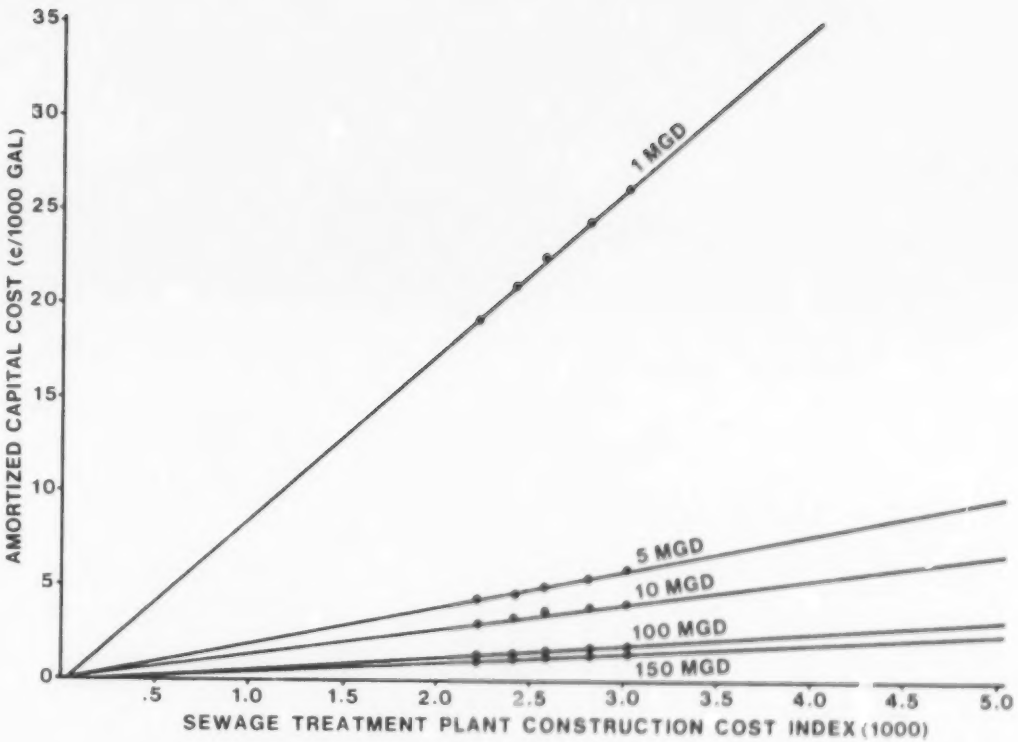

FIGURE 41. AMORTIZED CAPITAL COST VERSUS CONSTRUCTION COST INDEX

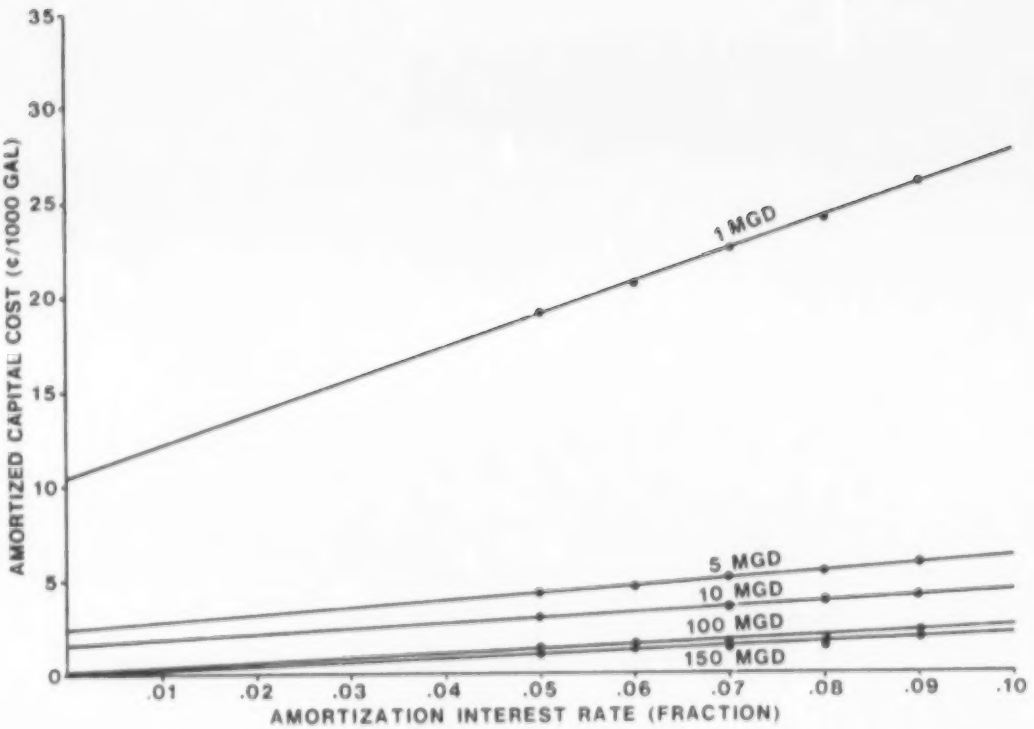

FIGURE 42. AMORTIZED CAPITAL COST VERSUS AMORTIZATION INTEREST RATE

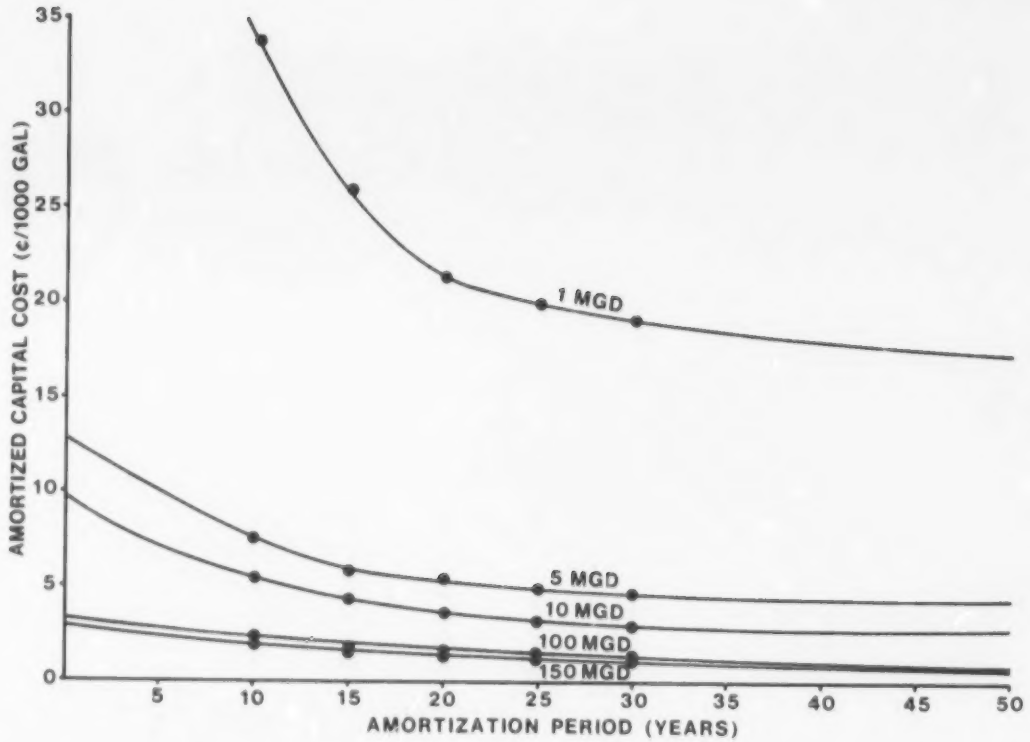

FIGURE 43. AMORTIZED CAPITAL COST VERSUS AMORTIZATION PERIOD

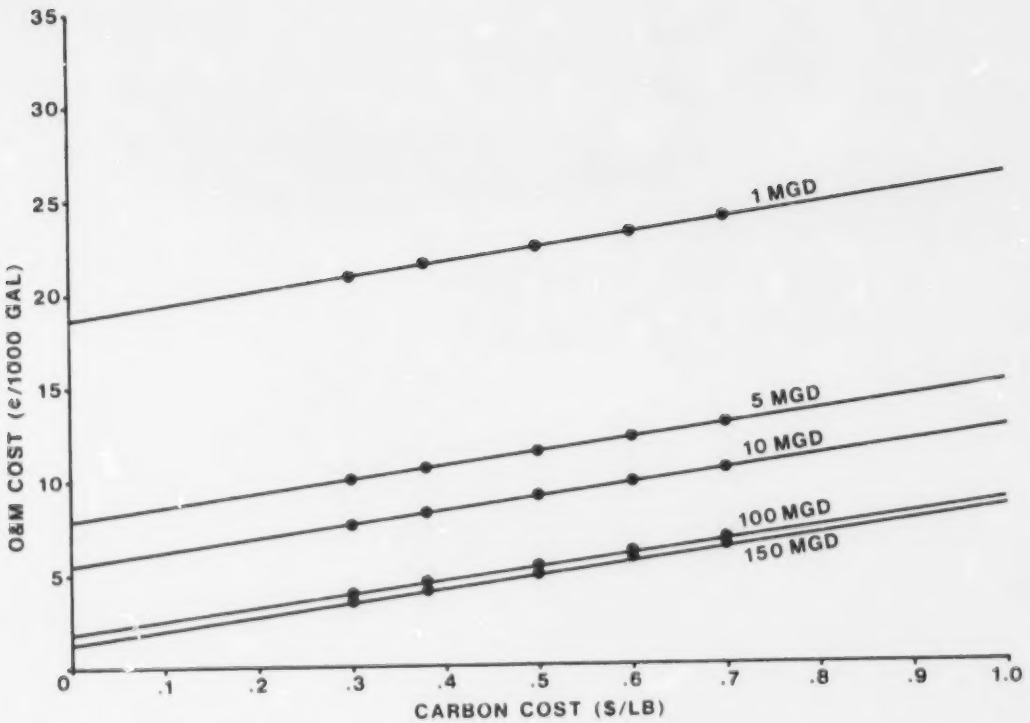

FIGURE 44. O&M COST VERSUS CARBON COST

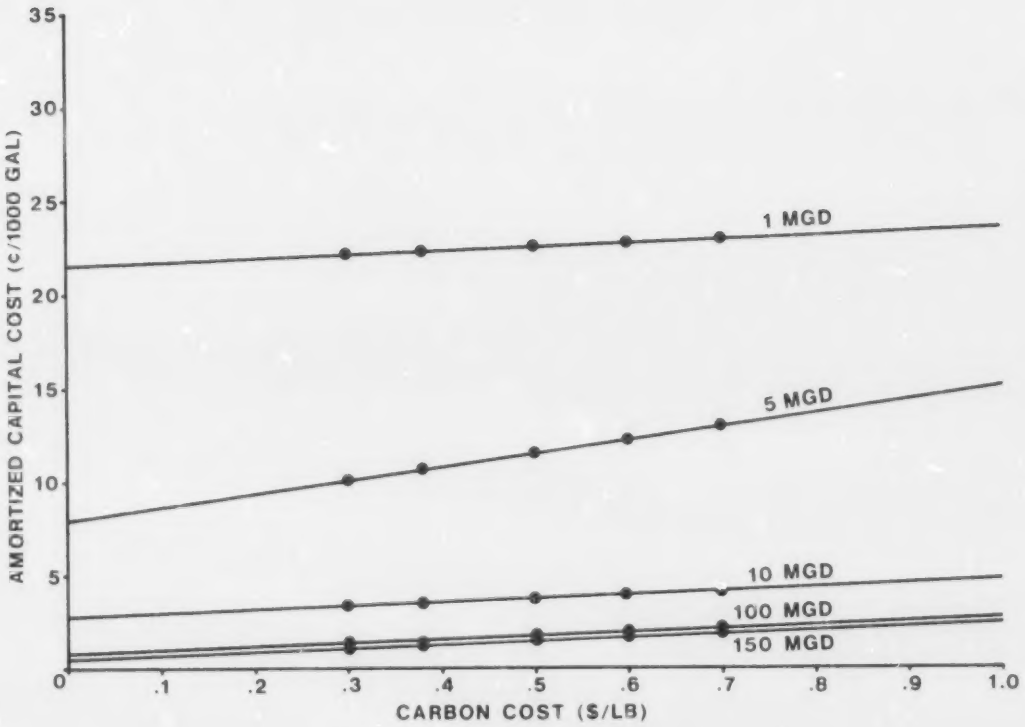

FIGURE 45. AMORTIZED CAPITAL COST VERSUS CARBON COST

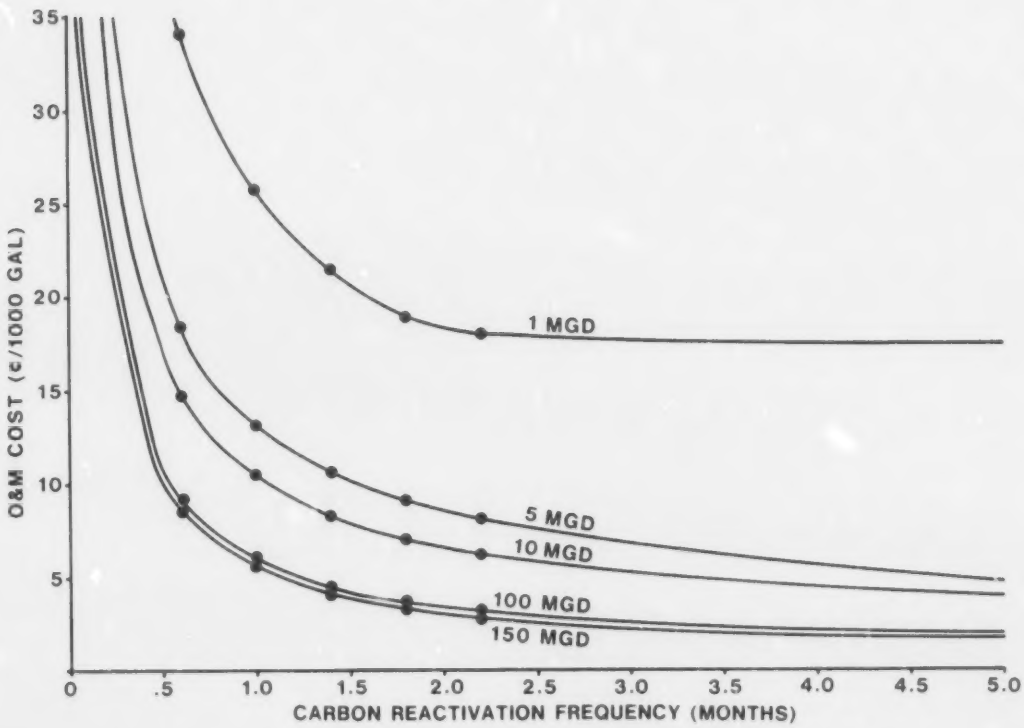

FIGURE 46. O&M COST VERSUS REACTIVATION FREQUENCY

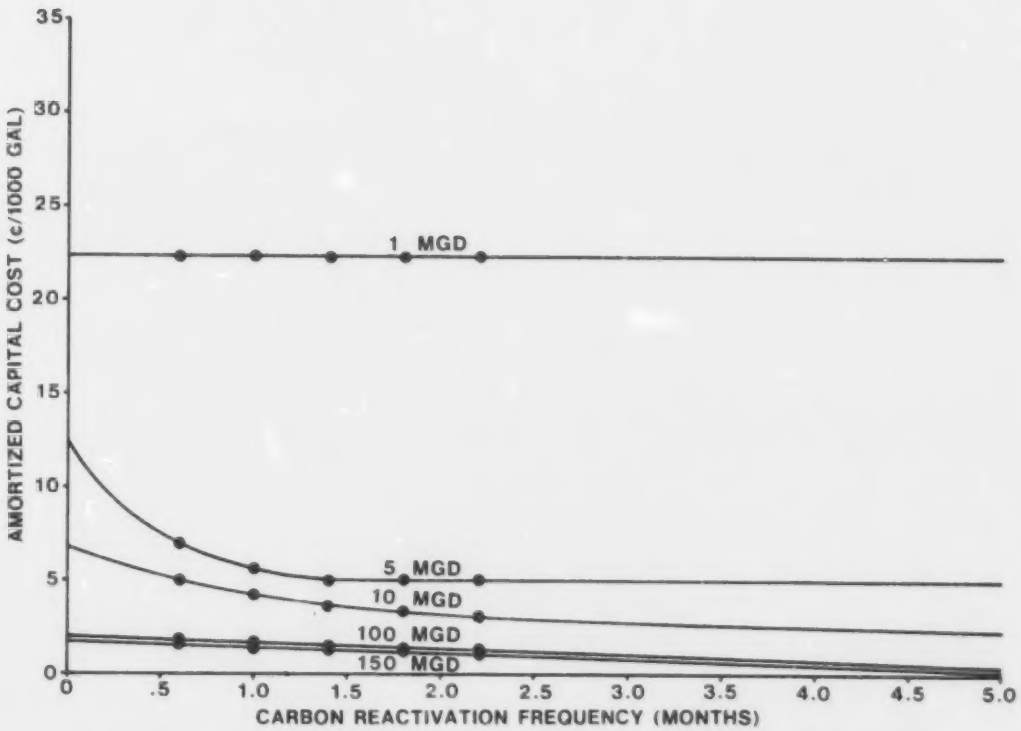

FIGURE 47. AMORTIZED CAPITAL COST VERSUS REACTIVATION FREQUENCY

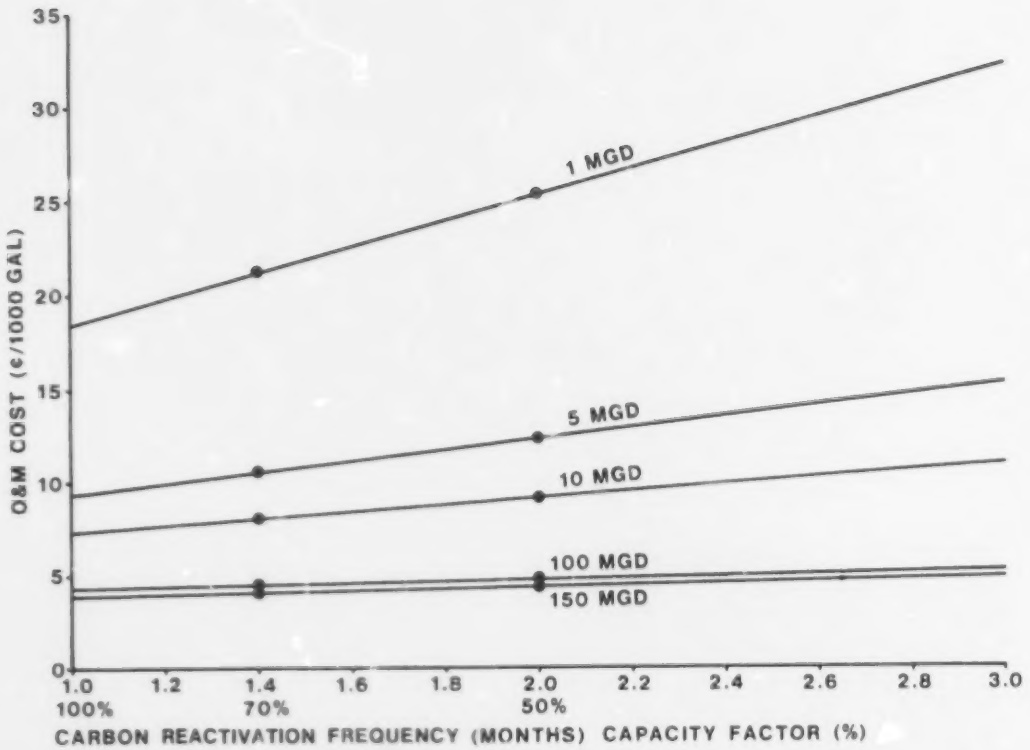

FIGURE 48. O&M COST VERSUS INTERACTION BETWEEN REACTIVATION FREQUENCY AND CAPACITY FACTOR

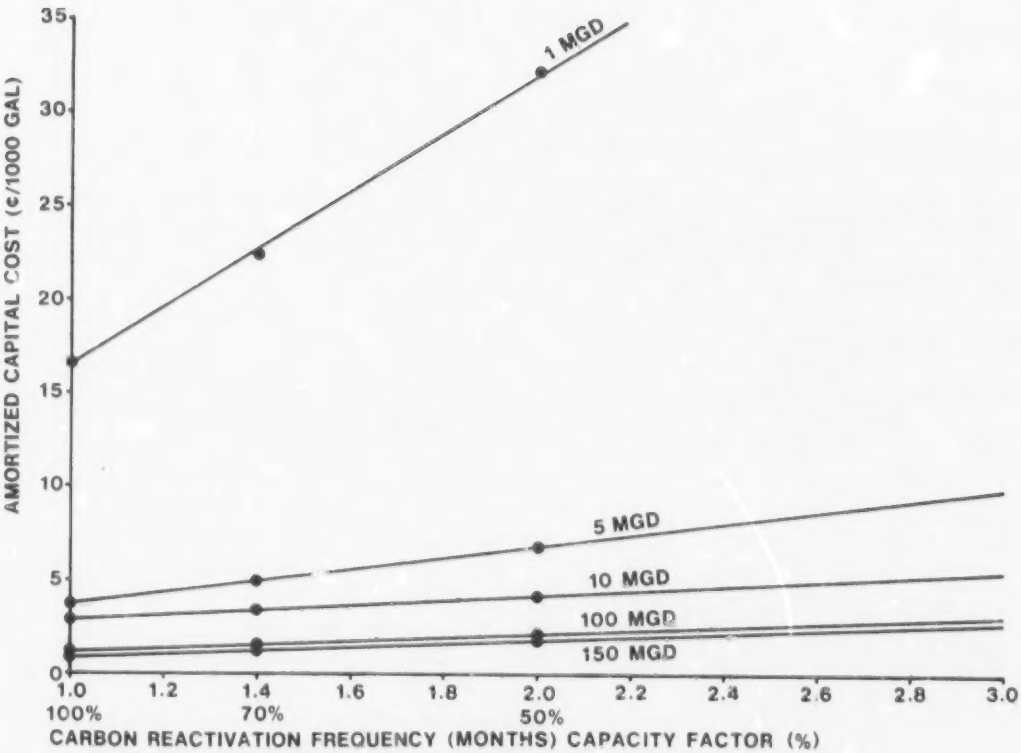

FIGURE 49. AMORTIZED CAPITAL COST VERSUS INTERACTION BETWEEN REACTIVATION FREQUENCY AND CAPACITY FACTOR

GAC system cost (5 percent) = 1.5 + [4.5 - 4.5 (.147)] (4)

= 5.3¢/1000 gal (5)

Figure 50 illustrates the percent change in cost for 1, 5, 10, 100, and 150 mgd systems that results from various activated carbon losses.

In the above equations, Amortized Capital cost remains constant as activated carbon loss affects only O & M cost. Some of the parameters, such as amortization period, have a multiplicative effect, as will be illustrated below. Assuming that amortization period, which affects only Amortized Capital cost, is in one case 10 years (150.9 percent) and in another case 30 years (85.4 percent), yields the following when compared with the standardized value of 1.5¢/1000 gal:

GAC system cost (10 years) = (1.5)(1.509) + 4.5 (6)

= 7.5¢/1000 gal (7)

GAC system cost (30 years) = (1.5)(0.854) + 4.5 (8)

= 5.8¢/1000 gal (9)

Equations 6 through 9 illustrate how the multiplicative factor affects Amortized Capital cost.

Table 10 contains the percentage change in O & M cost that results from setting the level for each design parameter at 50 percent, and at 150 percent (for a 100 mgd plant), of standard values. Table 11 contains the same information for Amortized Capital cost (for a 100 mgd plant). It should be noted that some of the parameters, such as carbon cost, affect both Amortized Capital and O & M cost.

The net effect of setting the design value for each parameter at the high and low values is shown in Table 12. Using the values shown in Table 12 the O & M and Amortized Capital costs are calculated as shown below for a 100 mgd plant.

Additive Modifications	High	Low
Amortized Capital Cost (¢/1000 gal):	1.5 + 1.5 (0.664)	1.5 - 1.5 (0.730)
Sum	2.5	0.4
O & M (¢/1000 gal):	4.5 + 4.5 (0.675)	4.5 - 4.5 (.576)
Sum	7.5	1.91

Using the above values the total cost can be calculated as follows:

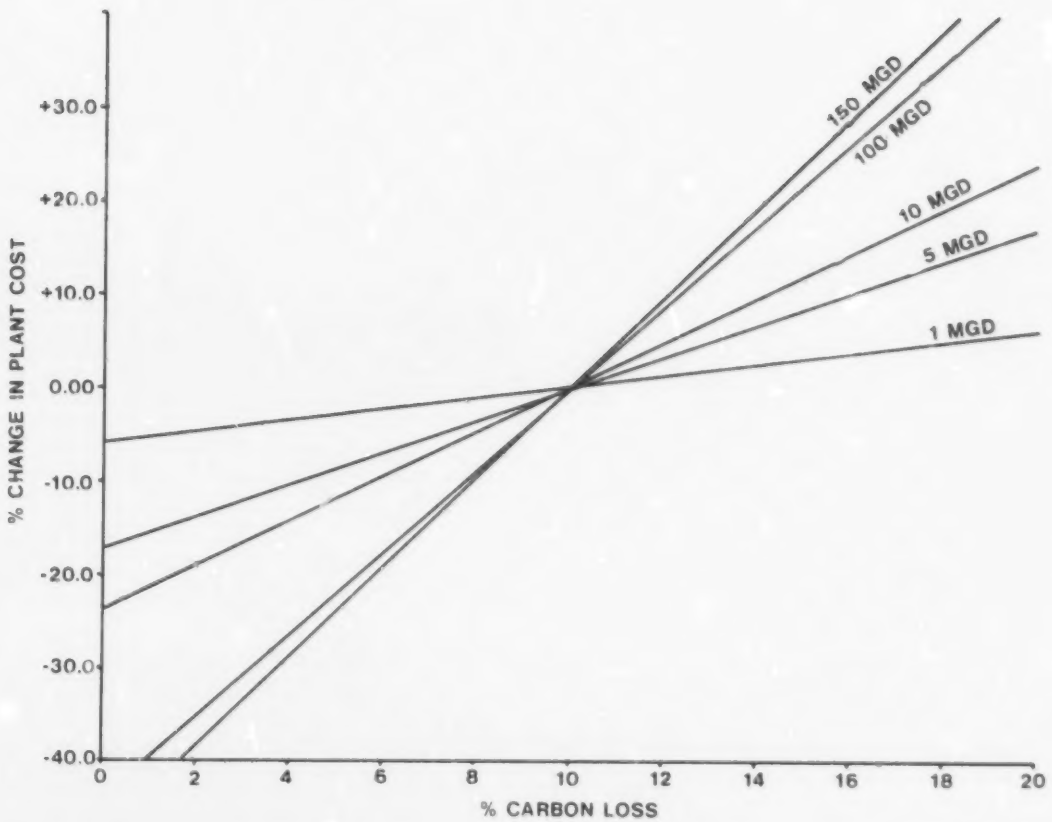

FIGURE 50. PERCENT CHANGE IN PLANT COST VERSUS CARBON LOSS

TABLE 10. DESIGN PARAMETERS AFFECTING O & M COSTS (100 mgd)

Parameters Affecting O & M Costs - Additive	Values	Percent Change
Carbon Loss per Reactivation Cycle (percent)	15	29.6
	10	0
	5	14.7
Carbon Cost (c/lb)	54	16.9
	38	0
	19	-22.0
Fuel Cost ($/mil BTU)	1.89	4.0
	1.26	0
	0.63	-3.8
Power Cost (c/KWH)	1.5	0.6
	1.0	0
	1.5	-0.6
Direct Hourly Wage Rate ($/hr)	7.78	15.9
	5.19	0
	2.60	-15.9
Wholesale Price Index	267	6.0
	178	0
	89	-5.0
Parameters Affecting O & M Costs - Multiplicative		
Reactivation Frequency (weeks between)	3	145.9
	6	100.0
	9	72.1
Capacity Factor (percent)	50	105.2
	70	100.0
	100	92.4

TABLE 11. DESIGN PARAMETERS AFFECTING AMORTIZED CAPITAL COSTS (100 mgd)

Parameters Affecting Amortized Capital Cost - Additive	Values	Percent Change
Carbon Cost (c/lb)	54	16.9
	38	0
	19	-22.0
Construction Cost Index	385	49.5
	257	0
	125	-51.0
Parameters Affecting Amortized Capital Cost - Multiplicative		
Amortization Period (yr)	10	150.9
	20	100.0
	30	85.4
Interest Rate (percent)	10.5	127.3
	7	100.0
	3.5	73.0
Reactivation Frequency (weeks between)	3	121.5
	6	100.0
	9	91.5
Capacity Factor (percent)	50	128.9
	70	100.0
	100	76.4

TABLE 12. NET EFFECT FOR SETTING DESIGN PARAMETERS AT HIGH AND LOW LEVELS (100 mgd)

Additive Factors for O & M	High (percent)	Low (percent)
Loss per Reactivation	29.5	-14.7
Carbon Cost	16.9	-22.0
Fuel Cost	4.0	- 3.8
Power Cost	0.6	- 0.6
Hourly Wage Rate	15.9	-15.9
Wholesale Price Index	0.6	- 0.6
Sum	+67.5	-57.6
Additive Factors for Amortized Capital Cost		
Carbon Cost	16.9	-22.0
Construction Cost Index	49.5	-51.0
Sum	+66.4	-73.0
Multiplicative Factors for O & M		
Reactivation Frequency	1.459	0.721
Hydraulic Load	1.052	0.924
Product	1.535	0.666
Multiplicative Factors for Amortized Capital Cost		
Amortization Period	1.509	0.854
Interest Rate	1.273	0.730
Reactivation Frequency	1.215	0.915
Hydraulic Load Factor	1.289	0.764
Product	3.008	0.436

Multiplicative Modifications	High	Low
Amortized Capital (¢/1000 gal)	(2.5)(3.008)	(0.4)(0.436)
Product	7.5	0.17
O & M (¢/1000 gal)	(7.5)(1.535)	(1.91)(0.666)
Product	11.5	1.27
Sum	19¢/1000 gal	1.44¢/1000 gal

Adding the final results for Amortized Capital and O & M costs yields a high value of 19¢/1000 gal and a low value of 1.44¢/1000 gal. These results illustrate the extremes which might result from localized conditions.

As can be seen from Figures 32 and 33, unit costs associated with small treatment systems are extremely high. The bulk of the Amortized Capital costs are for on-site reactivation facilities, which suggests the possibility that for small plants some alternative to on-site reactivation should be explored. One possibility would be to dispose of exhausted activated carbon and to purchase new carbon. The cost of disposal for a plant operating at 70 percent capacity factor, with a period between reactivation of 1.4 months, is shown below:

$$\text{Disposal cost} = \frac{(865 \text{ cu ft})(\text{No. of filters})(30 \text{ lb})(8.57 \frac{\text{reactivations}}{\text{yr}})(38\text{¢/lb})}{(\text{flow in mgd})(365 \text{ days/yr})(0.70)}$$

Disposal cost = 33.1¢/1000 gal

The above value can be compared to on-site reactivation costs for a 1, 5, 10, 100, and 150 mgd plant operating at 0.7 load factor with once-per-1.4 months reactivation (Figure 32). It can be seen from Figure 51 that disposing of exhausted carbon is actually cheaper than on-site reactivation for small plants (2 mgd or less) although it is obviously more expensive for larger plants.

Figure 51 suggests that another option that needs to be explored is that of regional reactivation. Regional reactivation consists of transporting the exhausted carbon to a central site where a reactivation furnace is located. This approach, which is particularly appropriate for small plants, will be explored in the following section.

Regional Reactivation

For the purposes of this analysis, three sets of regional reactivation conditions will be examined:

1. Regional reactivation systems consisting of off-site reactivation plants capable of processing carbon from the equivalent of 3100lb/day,

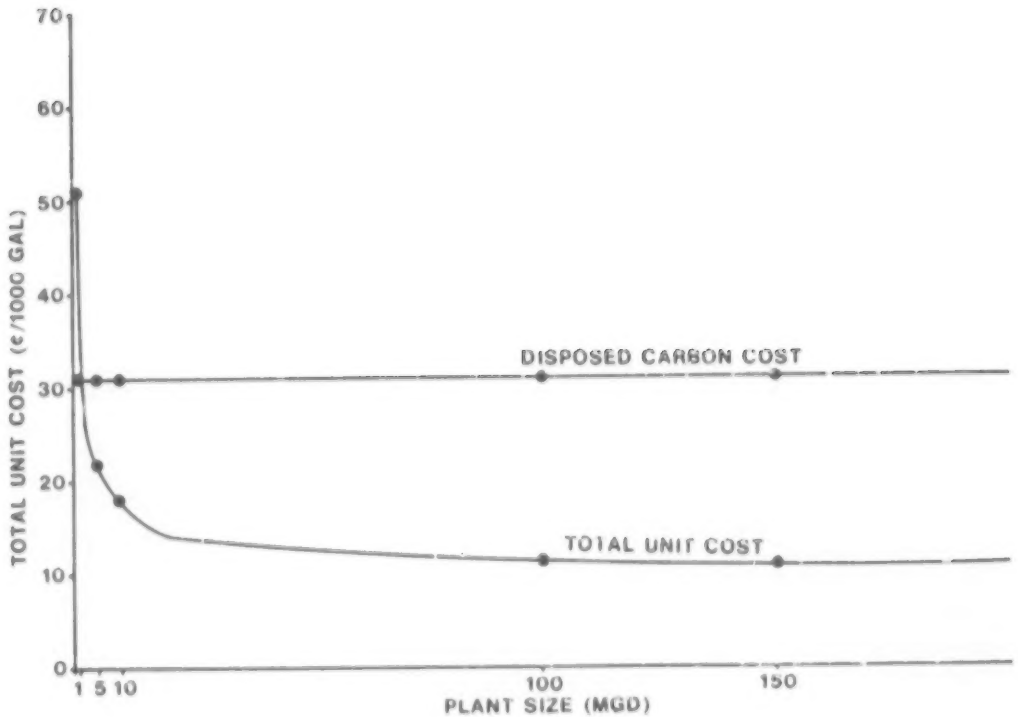

FIGURE 51. TOTAL UNIT COSTS VERSUS PLANT SIZE

6200 lb/day, 15,500 lb/day, 31,000 lb/day, and 62,000 lb/day reactivation facilities. These systems will be designated RP_1, RP_2, RP_3, RP_4, and RP_5, respectively.

2. Costs for individual plants shipping to these systems will be examined, based on the assumption that a number of plants are sharing these reactivation systems simultaneously. For example, the cost in ¢/1000 gal for a 1 mgd plant shipping carbon to a RP_1 and RP_2, and a 10 mgd plant transporting carbon to a RP_4 and RP_5 system will be calculated assuming that the various regional off-site reactivation systems are being used to capacity.

By transporting carbon to a regional reactivation center a small plant is able to take advantage of the economies of scale inherent in a larger reactivation furnace, although there is a debit associated with the transportation cost required to get the carbon to the site. The assumptions regarding the operation of the plants are the same as those in Table 9 (for example, 70 percent load factor and 1.4 months between reactivation). The costs associated with the water treatment plant will be as follows: the initial activated carbon purchase (twice the capacity of the treatment plant, as one batch of carbon is being reactivated while the other is in place) and the make-up carbon (loss assumed at 10 percent per replacement cycle due to handling); transportation costs, which will be assumed as $.10/ton-mile, and a proportionate share of the off-site reactivation costs which will consist of furnace capital and operating costs, assuming a 10 percent loss of activated carbon during the reactivation process. Table 13 contains the costs associated with the initial carbon cost, and the carbon loss as well as the equivalent carbon reactivation requirements per day in lb/day for each plant size. Figures 52 and 53 show the total construction and operating costs for an off-site reactivation furnace based on lb/day of reactivation. It is assumed in this analysis that the Amortized Capital and O & M costs for reactivation system are divided equally among the number of plants shipping carbon to it. For example, if five 1 mgd plants are shipping to an RP_1 system, the cost will be higher than if ten 1 mgd plants are shipping carbon to RP_2 system.

Transportation costs are calculated as follows for a 1 mgd plant shipping carbon to a reactivation plant for a 30-mile round trip:

$$\text{Transport Cost} = \frac{(10¢/\text{ton-mile})(865 \text{ cu ft})(30 \text{ miles})(30 \text{ lb/cu ft})(\frac{\text{ton}}{2000})(8.57 \text{ react/yr})}{(365 \text{ days})(1 \text{ mgd})(0.70)}$$

$$= .131¢/1000 \text{ gal (30-mile round trip)}$$

On a per-gal-mile basis, the cost is

$$¢/\text{gal-mile} = (.131¢/1000 \text{ gal})(30 \text{ mile})$$

$$= .0044¢/1000 \text{ gal-mile}$$

TABLE 13. CARBON COSTS AND REACTIVATION REQUIREMENTS FOR REGIONAL REACTIVATION SYSTEMS

Plant Size (mgd)	Initial Carbon Requirements (lb)	Annual Cost ($)	Make-up Carbon ($)	Reactivation Requirements (lb/day)
1	51,900	1,861.4	7,254	617.86
5	259,500	9,307.1	35,319	3,089.29
10	519,000	18,614.1	69,835	6,178.57
100	5,190,000	186,141.3	672,321	61,785.71
150	7,785,000	279,212.0	1,001,758	92,678.56

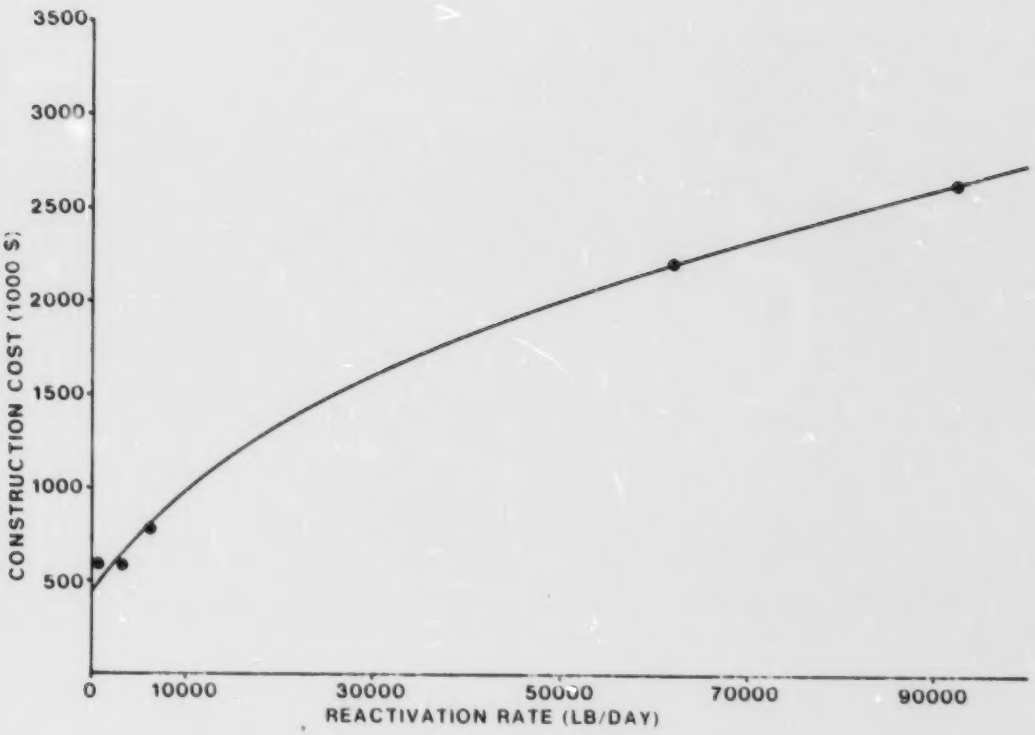

FIGURE 52. CONSTRUCTION COST FOR CARBON REACTIVATION SYSTEM VERSUS REACTIVATION RATE

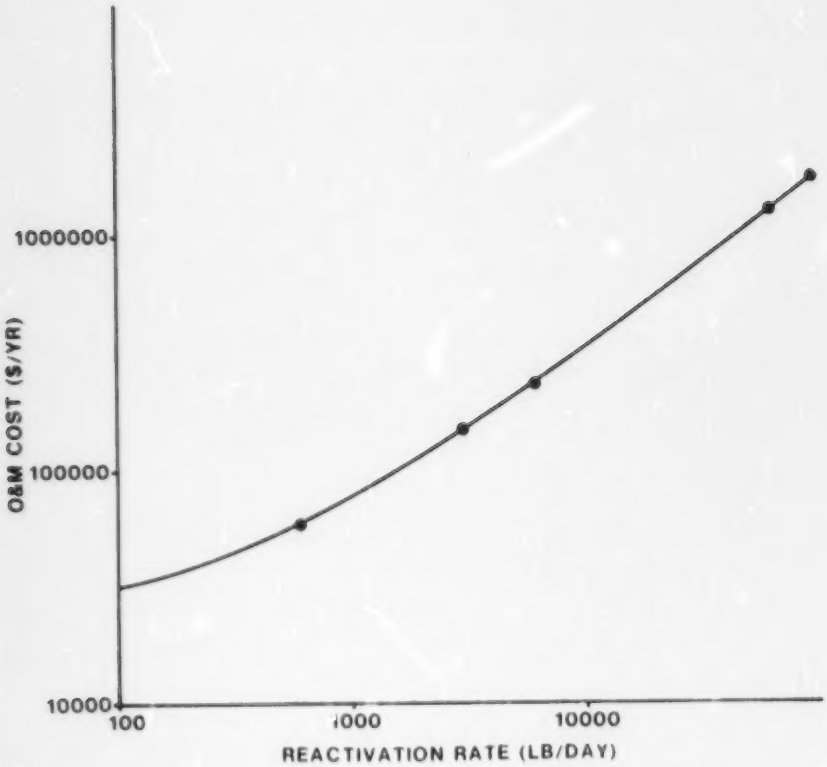

FIGURE 53. O&M COST FOR CARBON REACTIVATION SYSTEM VERSUS REACTIVATION RATE

The Amortized Capital cost and annual O & M cost for the off-site reactivation systems are shown in Table 14. These costs can be assigned equally to the water treatment plants served. For example, RP_1 can serve five 1 mgd treatment plants and the total cost is divided by five, but for RP_2, which can serve 10 1 mgd plants, the total annual cost is divided by 10. Table 15 contains the flow in mil gal/yr and the total allocated cost plus the initial activated carbon and makeup costs for each plant reactivation configuration. As can be seen from Table 15, the unit cost for a 1 mgd plant sending carbon to a regional reactivation furnace serving five plants is higher than for a 1 mgd plant sending carbon to a system serving 10 plants due to economies of scale in the reactivation system. Transportation costs must also be considered as in the following discussion.

Figure 54 shows the distance-related costs associated with the regional reactivation system for 1 mgd plants sending carbon to a RP_1 and RP_2 reactivation system, as compared to on-site reactivation system, and the slope of the curve shows that carbon can be transported for many miles before an on-site system becomes cost effective. Figures 55 and 56 show similar conditions for 5 mgd plants and 10 mgd plants transporting to RP_3 and RP_4, and RP_4 and RP_5 systems, respectively. It can be seen that for a 10 mgd plant it also is cost effective to transport spent carbon over relatively long distances, however, the gap between on-site and transporting off-site narrows at this level. Figure 57 shows the impact of variations in transportation cost on the total cost of a 10 mgd plant transporting waste to a RP_4 system.

An alternative to replacing carbon in the filter shell is to build separate carbon contactors as an integral part of the treatment system. A discussion of this option is presented in the following section.

Separate Contactor System

In the discussion to this point the costs presented have been based on the assumption that carbon would replace sand in a filter plant. Therefore, no Amortized Capital and O & M costs associated with separate carbon contactors have been included in the analysis. It is very likely that operating in such a manner is inconvenient and inefficient, causing higher carbon losses due to excessive handling. A contactor system may be tailored specifically for a given treatment plant operation. The assumptions used for the contactor system analysis are as follows (Table 16): two contactors connected in series, a contact time of nine minutes and a corresponding recycle frequency of one-per-2.8 months, bed depths of 20 ft, and a carbon loss of 5 percent per reactivation cycle. Figure 58 compares the costs for a separate contactor system versus replacement of carbon as filter media.

Replacing sand by carbon represents a short-term possibility for water treatment plants with low capital investment but high operating costs. A separate contactor system represents a longer term and permenent solution with higher capital investment requirements but with lower operating costs as shown in Table 17. These capital investment requirements are discussed in the following section.

TABLE 14. AMORTIZED CAPITAL AND OPERATING COSTS FOR OFF-SITE REACTIVATION SYSTEMS

Reactivation System	Reactivation Requirement (lb/day)	Construction Cost ($)	Amortized Capital Cost ($)*	Annual O & M Cost ($)
RP_1	3,089.27	700,000	66,080	180,000
RP_2	6,178.57	820,000	77,408	240,000
RP_3	15,446.35	1,350,000	127,440	460,000
RP_4	30,892.85	1,630,000	153,872	750,000
RP_5	61,785.71	2,200,000	207,600	1,130,000

* 7 percent interest, 20-yr amortization period.

TABLE 15. REACTIVATION SYSTEMS COST FOR AN INDIVIDUAL PLANT

Regional Reactivation		Flow per Plant (mil gal/yr)	Total Annual Cost ($)	Unit Cost (¢/1000 gal)
Regional Reactivation Configuration	Total No. of Plants			
1 - RP_1	5	225	56,470.00	25.1
1 - RP_2	10	225	38,995.00	17.3
5 - RP_3	5	1277.5	162,114.10	12.7
5 - RP_4	10	1277.5	135,013.10	10.6
10 - RP_4	5	2555.0	269,321.0	10.5
10 - RP_5	10	2555.0	222,217.1	8.7

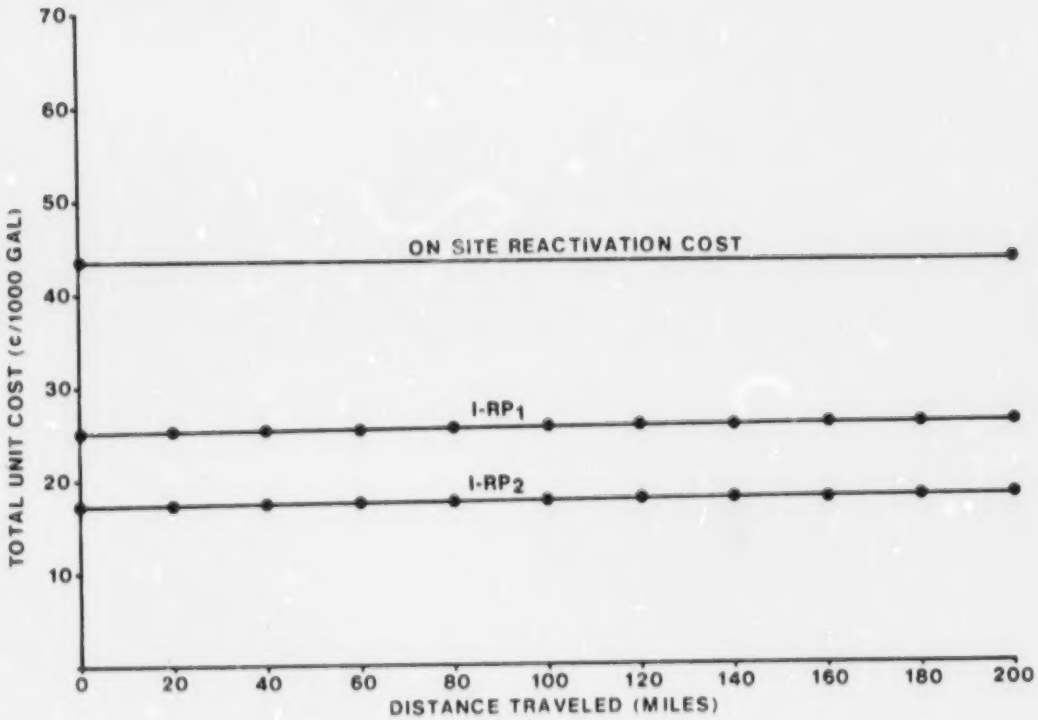

FIGURE 54. COST OF TRANSPORTING CARBON FROM A 1 MGD PLANT TO REGIONAL REACTIVATION SITE VERSUS DISTANCE IN MILES

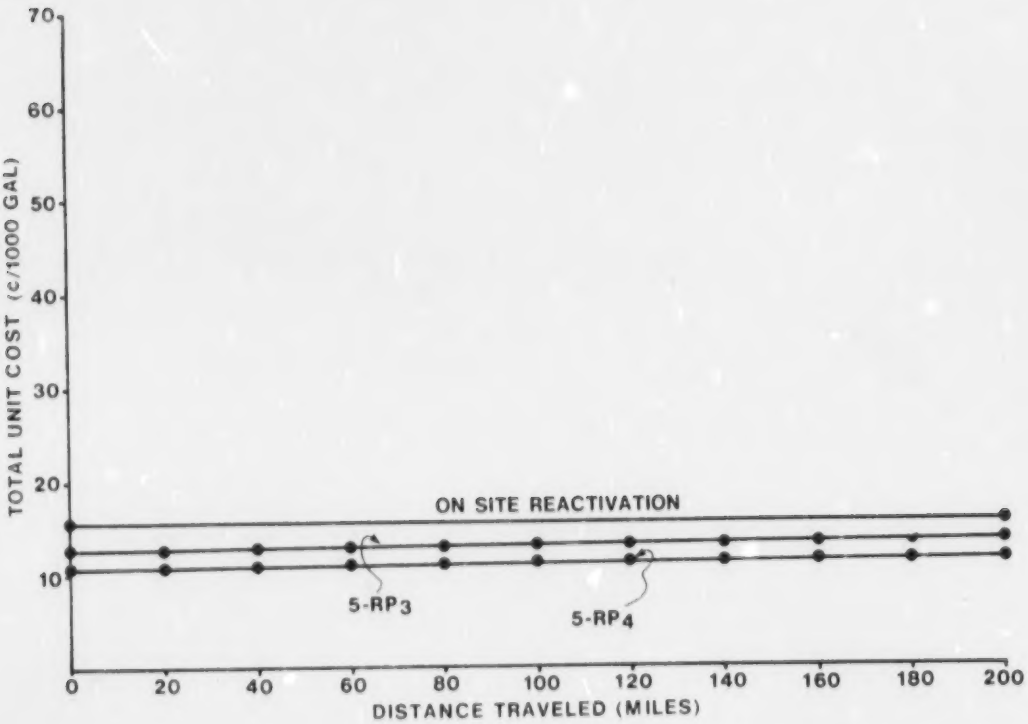

FIGURE 55. COST OF TRANSPORTING CARBON FROM A 5 MGD PLANT TO REGIONAL REACTIVATION SITE VERSUS DISTANCE

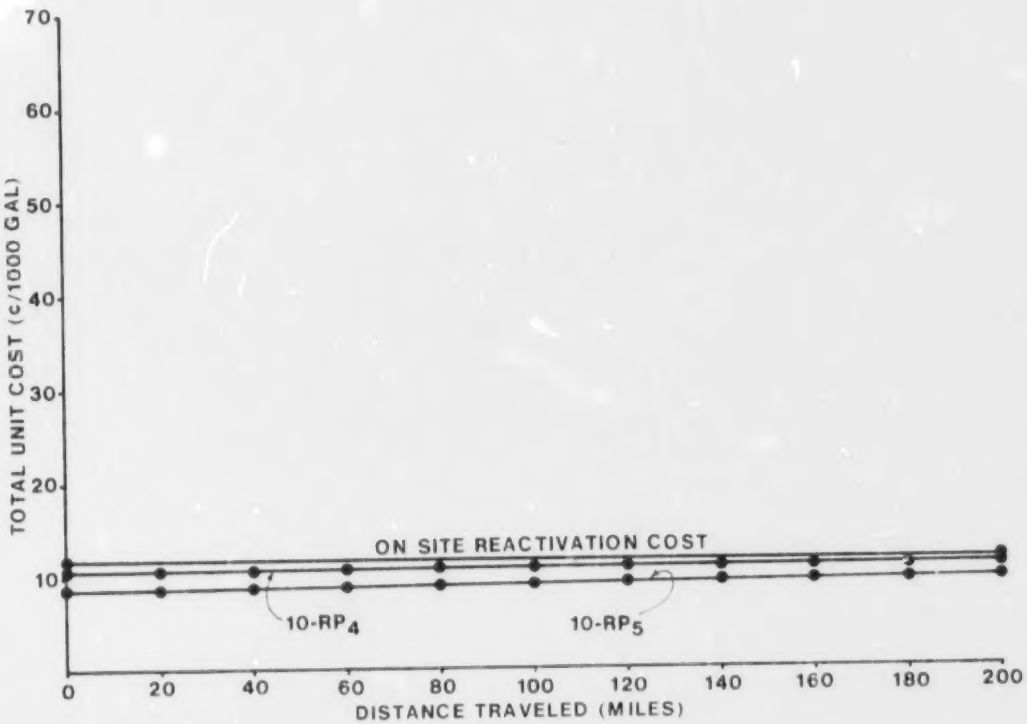

FIGURE 56. COST OF TRANSPORTING CARBON FROM A 10 MGD PLANT TO REGIONAL REACTIVATION SITE VERSUS DISTANCE IN MILES

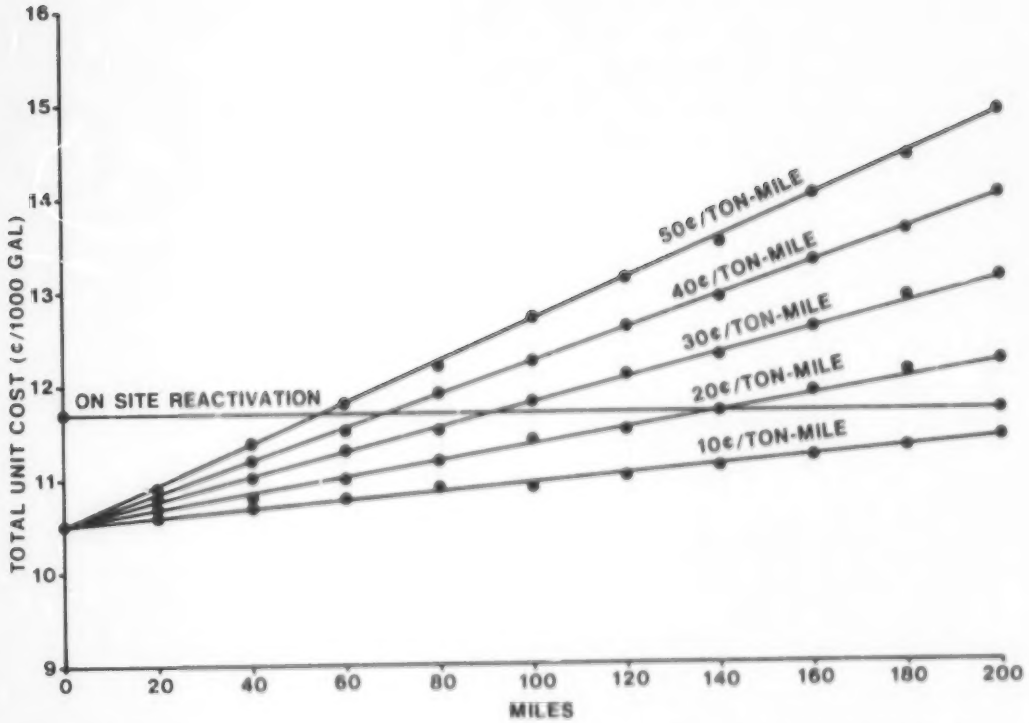

FIGURE 57. THE SENSITIVITY OF REACTIVATION COSTS TO TRANSPORTATION COST VARIATIONS

TABLE 16. ASSUMPTIONS FOR SEPARATE CONTACTOR SYSTEMS

Item	Plant Capacity (mgd)				
	1	5	10	100	150
Number of Contactors	2	4	8	28	42
Hydraulic Loading (gal/min/sq ft)	4.87	5.42	5.42	5.57	5.57
Diameter Contactors (ft)	8	12	12	20	20
Depth of Contactors (ft)	13	13	13	14	14
Vol. of Granular Activated Carbon per Contactor (cu ft)	653.1	1469.5	1469.5	4396.0	4396.0
Apparent Contact Time (min)	9	9	9	9	9
Reactivation Frequency (months) at 70 percent Capacity	2.8	2.8	2.8	2.8	2.8
Activated Carbon Loss/ Reactivation (percent)	5	5	5	5	5

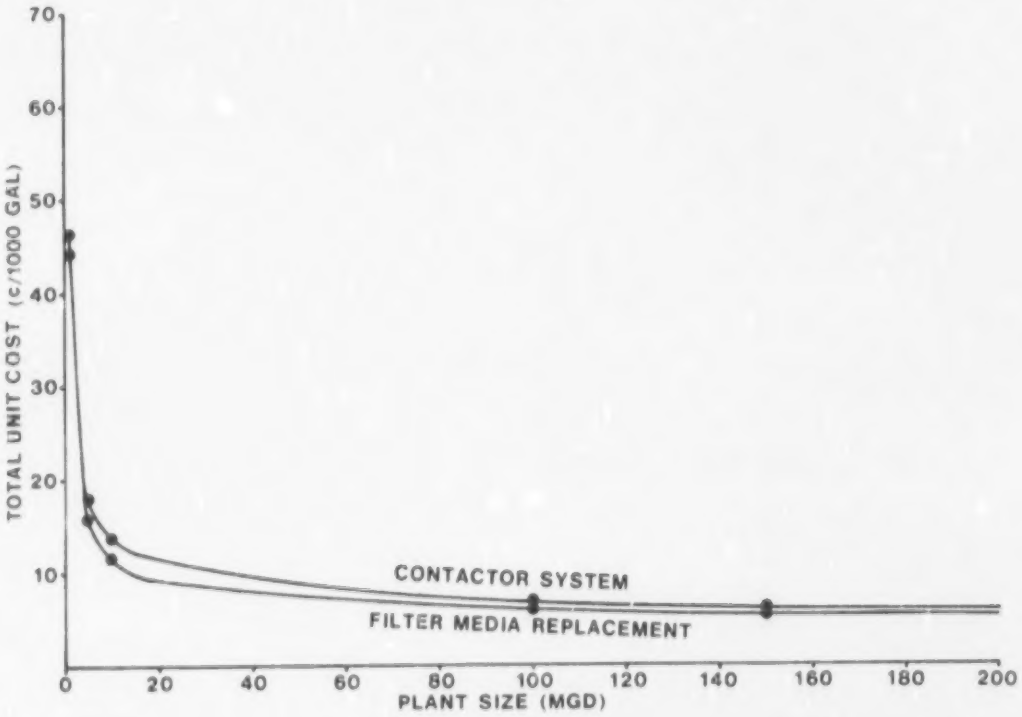

FIGURE 58. COMPARISON OF COSTS BETWEEN CONTACTOR SYSTEM AND MEDIA REPLACEMENT VERSUS PLANT CAPACITY

TABLE 17. AMORTIZED CAPITAL AND O & M COSTS FOR CONTACTOR VERSUS FILTER MEDIA REPLACEMENT (¢/1000 gal)

System	1 mgd	5 mgd	10 mgd	100 mgd	150 mgd
			Amortized Capital Costs		
Media Replacement	19.5	5	3.5	1.5	1.1
Contactors	30.2	10.2	8.2	4.3	4.1
			Operating and Maintenance Costs		
Media Replacement	21.5	10.5	8.2	4.5	4.0
Contactors	16.1	7.3	5.4	2.4	2.2
			Total Cost		
Media Replacement	41.1	15.5	11.7	6.0	5.1
Contactors	46.3	17.5	13.6	7.3	6.3

Capital Investment

All of the cost data presented to this point in the analysis have been in terms of unit costs (including Amortized Capital and O & M costs). It is important to present a different perspective by examining total investment costs. Separate contactor systems, as can be seen from Table 17, are more capital intensive then replacing the filter media by activated carbon. To build these systems, utilities must raise considerable amounts of initial capital. Table 18 summarizes for 1, 10, and 100 mgd plants the principal and total payback costs required for both types of GAC systems.

A major part of the capital investment for an on-site reactivation system is the furnace. Table 19 summarizes the estimated cost of these types of furnaces.

TABLE 19

ESTIMATED CONSTRUCTION COST OF GRANULAR ACTIVATED CARBON REACTIVATION FURNACES

Furnace Type	Capacity	Estimated Total Cost
Multiple-Hearth	5,000 lb/hr	$4.2 million
Infrared*	5,000 lb/hr	$0.8 million
Rotary Kiln	5,000 lb/hr	See note
Fluidized Bed*	5,000 lb/hr	$1.2 million

* Because furnaces of this size have not been manufactured, these estimates are very preliminary.

Note: Insufficient information is available to estimate a cost for this type of furnace.

Labor Costs for GAC Systems

The previous analysis points to one salient fact regarding the use of granular activated carbon. Unit costs for small plants reactivating on-site may be prohibitively expensive. It is obvious that plants in the 1 mgd design capacity should consider off-site reactivation in a regional facility.

All of the previous cost evaluations have been made for critical design conditions, such as a once-per-1.4 month reactivation cycle and capacity factors below 100 percent. These data have been computed for isolated systems. In a total treatment complex, however, there may be opportunities to share labor among several activities. For example, the laborers assigned

TABLE 18. INVESTMENT COSTS FOR GRANULAR ACTIVATED CARBON TREATMENT: REPLACEMENT OF MEDIA AND SEPARATE CONTACTORS (THOUSANDS OF DOLLARS)*

Item	1 mgd		10 mgd		100 mgd	
	Media Replacement	Contactor	Media Replacement	Contactor	Media Replacement	Contactor
Principal	610	857	884	2,328	4,247	12,207
Total Cost (Principal & Interest)	1,100	1,543	1,788	4,190	7,665	21,973

* Based on 7 percent interest and 20-yr amortization period.

to groundskeeping or general labor might be utilized in the reactivation activity. Such a joint use of labor might realize genuine savings, particularly in a small plant. Table 20 displays the percentage of total costs for plants with on-site reactivation which is made up of labor costs. It can be seen that for small plants with on-site reactivation, labor costs account for over 40 percent of the total cost.

SUMMARY AND CONCLUSIONS

It is obvious from the data presented in this report that chlorination is the cheapest of all of the treatment technologies that might be used for disinfection. Table 21 summarizes the values for a 1, 5, 10, 100, and 150 mgd plant for all of the treatment alternatives examined in this report.

As chlorination under certain conditions causes chloroform, a potential carcinogen, in drinking water, planning and operating agencies must examine alternatives to the chlorination process. These alternatives might take the form of disinfection techniques other than chlorination, or of trihalomethane removel techniques such as aeration, or of organic removal techniques such as granular activated carbon. Hopefully, this report will assist in making these evaluations.

TABLE 20. LABOR COSTS FOR 1, 10, and 100 mgd GAC SYSTEMS REACTIVATING ON-SITE (FILTER SHELL REPLACEMENT)

Plant Capacity	Capacity Factor	Total Cost $/yr	Labor Cost $/yr	Percent Labor Cost
5	.7	199,915.97	91,385	46
10	.7	302,103.2	124,724	41
100	.7	2,098,677.0	421,756	20

TABLE 21. COMPARISON AMONG SYSTEMS (¢/1000 gal)

System	1 mgd	5 mgd	10 mgd	100 mgd	150 mgd
Chlorination	3.6	1.6	1.2	0.7	0.6
Chlorine Dioxide	3.8	2.0	1.7	1.3	1.3
Ozonation (air)	6.3	2.3	1.6	0.8	0.8
Ozonation (oxygen)	7.7	2.5	1.8	0.9	0.8
Aeration	22.3	14.6	12.8	9.0	8.5
Granular Activated Carbon (Media Replacement)	41.0	15.5	11.7	6.0	5.1
Granular Activated Carbon (Contactors)	46.3	17.5	13.6	6.7	6.3

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